



Improving Myoelectric Prosthetic Hand Control via a Multifaceted, User-Centred Approach

Digby Eric Chappell

July 2024

Department of Computing

Imperial College London

Submitted in part fulfilment of the requirements for the degree of

Doctor of Philosophy of Imperial College London

and the Diploma of Imperial College London

Abstract

This thesis investigates methods of improving myoelectric prosthetic hand control as a complete human-in-the-loop control system via a multifaceted approach; in terms of the range of contributions to core myoelectric control elements, and also the diverse examined physical and psychological effects. Myoelectric prostheses have been the subject of over 75 years of attention in research, development, and even fiction. Despite this, user rejection is common, with issues such as discomfort and functionality as prevalent now as they were decades ago. This thesis aims to address these problems by challenging established ideologies and by examining key aspects of the entire human-in-the-loop system, equally weighting user training, end-effector design, and control algorithm development, and evaluating the physical and psychological effects to a more complete level than is seen in existing literature.

First, myoelectric prosthetic hand control is introduced and literature reviewed. Next, a robot-enhanced virtual reality platform for prosthetic hand training is presented, which demonstrates higher quality and more representative training than virtual reality alone. Chapter three outlines two personalised discrete myoelectric controllers with comparative performance to computationally heavy controllers, the second achieving near-instant calibration from minimal data. Chapter four presents a closed-loop continuous myoelectric controller, which combines a proprioceptive feedback armband with a multi-degree-of-freedom continuous controller which requires minimal user data, leading to improvements in isolated control and sensory tasks, precision grasping, and faster psychological embodiment. Chapter five examines prosthetic hand design itself, and presents grasp-specific and task-specific prostheses; the former achieves power and precision grasps with minimal complexity, while the latter dramatically outperform a conventional prosthesis on targeted tasks.

The goals of this thesis are to encourage practitioners to view myoelectric prosthetic hand control as the complex, human-centred system that it is, and to provide key starting points toward improving myoelectric control, and ultimately improving end-user outcomes.

Acknowledgements

This thesis would not have been possible without the help and kindness of a long list of people.

First and foremost, I would like to thank every person that participated in the studies completed during my PhD, in particular those who have upper limb difference. Many researchers in the field of prosthetics will agree that finding and connecting with participants is a challenge, so the time, effort, and (brutally) honest feedback that each participant gave is hugely appreciated and shaped my research in ways that I could never have expected. Alongside this, I would like to thank the charities and organisations that helped connect me with participants and/or raised awareness of my research: The Alex Lewis Trust, the Physical Disability Rugby League, Disability Sport Wales, Reach, and the Amputation Foundation — all of whom do amazing work supporting those with limb difference and their families.

I would like to extend my gratitude to my three supervisors, Dr Nicolas Rojas, Dr Petar Kormushev, and Professor Fernando Bello. Nicolas, you have been a fantastic supervisor and friend, and you have shaped me into a better researcher for it. Petar, thank you for creating the opportunity for me to do this PhD and for your support throughout its duration. Fernando, your pastoral support as well as your detailed feedback on my work has been appreciated on many occasions.

I have been fortunate to work alongside several great groups of people during my PhD: my labmates in the REDS Lab, the Robot Intelligence Lab, and the SiMMS Research Group, my cohort in the AI for Healthcare CDT, many members of the Morph Lab, and all of the students that have passed through the Dyson School of Design Engineering basement since October 2019. All of these have created a supportive, lively atmosphere, and I have made many lifelong friends.

Finally, I would like to thank my family, friends, and loved ones for their constant support and encouragement throughout my PhD. I couldn't have done it without you.

Statement of Originality

I hereby declare that, except where specific reference is made to the work of others, the contents of this dissertation are original and have not been submitted in whole or in part for consideration for any other degree or qualification at this, or any other university. Except where indicated by specific reference in the text, the work is the candidate's own work. Work done in collaboration with, or with the assistance of, others, is indicated as such. Any views expressed in the dissertation are those of the author.

The work presented hereafter is based on research carried out by the author at Imperial College London and it is all the author's own work except where otherwise acknowledged. No part of the present work has been submitted elsewhere for another degree or qualification.

Digby Chappell

July 2024

Copyright Declaration

The copyright of this thesis rests with the author. Unless otherwise indicated, its contents are licensed under a [Creative Commons Attribution Non-Commercial](#) license (CC BY-NC). Under this licence, you may copy and redistribute the material in any medium or format. You may also create and distribute modified versions of the work. This is on the condition that: you credit the author and do not use it, or any derivative works, for a commercial purpose. When reusing or sharing this work, ensure you make the licence terms clear to others by naming the licence and linking to the licence text. Where a work has been adapted, you should indicate that the work has been changed and describe those changes. Please seek permission from the copyright holder for uses of this work that are not included in this licence or permitted under UK Copyright Law.

Contents

List of Tables	vii
List of Figures	ix
1 Introduction	1
1.1 Motivation	1
1.2 Preliminaries	3
1.3 Publications	15
1.4 Thesis Structure	16
2 Improving User Ability with Traditional Controllers	17
2.1 Introduction	17
2.2 Related Work	20
2.3 Methods	21
2.4 Results & Discussion	29
2.5 Conclusions	32
3 Advancing Discrete Control	33
3.1 Introduction	33
3.2 Related Work	34
3.3 Embedded Discrete Control	36
3.4 Advanced Discrete Control with Minimal User Data	40
3.5 Conclusions	52
4 Achieving Continuous Control	54
4.1 Introduction	54
4.2 Related Work	56
4.3 Continuous Control	57
4.4 Closed-Loop Control	61
4.5 Evaluation	64

4.6	Results	68
4.7	Discussion	77
4.8	Conclusions	80
5	The Controlled Prosthesis	82
5.1	Introduction	82
5.2	Related Work	84
5.3	A Taxonomy of Real and Fictional Upper Limb Prostheses	86
5.4	Task-Specific Upper Limb Prostheses	88
5.5	Grasp-Specific Upper Limb Prostheses	97
5.6	Results	103
5.7	Discussion	111
5.8	Conclusions	114
6	Conclusions	115
6.1	Summary of Main Contributions	115
6.2	Strengths	117
6.3	Limitations	117
6.4	Future Work	118
	Bibliography	120
A	Appendix for Achieving Continuous Control	142
A.1	Tables	142
A.2	Figures	145
A.3	Post-Study Interview Transcripts	159
B	Appendix for The Controlled Prosthesis	237
B.1	Tables	237
B.2	Figures	239

List of Tables

4.1	Summary table of participant characteristics of participants with limb difference and identified factors that influence perception.	66
5.1	Results of the Soft Object Gripper Benchmark D. Items of clothing are grasped at a flat, non-boundary region, and grasp success rate is recorded.	110
A.1	Table of participant characteristics of individual participants with limb difference. For bilateral upper limb differences the side tested is shown in brackets, and details for the tested side are shown. Causes listed: congenital (C), traumatic injury (TI), planned surgery (PS). *Participant 002 acquired a higher level of ULD than their congenital level from further traumatic injury; the muscles of the upper arm were used as an alternative input. †Participants 005 and 009 were only able to activate two muscles in their residual limb. ‡Participant 008 acquired their ULD via planned surgery after a prior traumatic injury, and received targeted muscle reinnervation; the muscles of the upper arm were used. §Participants 001 and 010 had no functioning elbow joint. . . .	143
A.2	Characteristics of groups of participants without limb difference. Age, gender, and handedness of groups of participants without limb difference. For age, standard deviation is shown in brackets.	144
A.3	Prosthesis Embodiment Questionnaire for Upper Limb Prostheses. The questionnaire used to assess prosthesis embodiment for upper limb prostheses. Each question is answered using a 7-point Likert scale.	144
B.1	Characteristics of groups of participants without limb difference for each task. Age, gender, and handedness of groups of participants without limb difference. For age, standard deviation is shown in brackets.	237
B.2	Table of participant characteristics of individual participants with limb difference. For bilateral upper limb differences the side tested is shown in brackets, and details for the tested side are shown. Causes listed: traumatic injury (TI), planned surgery (PS). ¶Participant 2 acquired their ULD via planned surgery after a prior traumatic injury, and received targeted muscle reinnervation; the muscles of the upper arm were used. .	237

B.3	Prosthesis Embodiment Questionnaire for Upper Limb Prostheses. The questionnaire used to assess prosthesis embodiment for upper limb prostheses. Each question is answered using a 7-point Likert scale.	238
-----	--	-----

List of Figures

1.1	Human-in-the-loop control of myoelectric prostheses, blocks are labelled with the chapters in which developments are made. a The user’s internal control loop, where prior knowledge, contextual information, sensory information, and the predicted response of the prosthesis are inputs to produce a user intention, and consequently an internal command for the muscles of the user’s residual limb. b The process of motor signals from the user’s brain producing recorded EMG signals. c The conventional myoelectric control system; a myoelectric control algorithm produces a command action for the prosthetic end effector, which is executed in the environment. d Low-level control loop, consisting of the low-level controller of the end effector of the prosthesis, and any sensors such as motor encoders that close this loop. e External sensory feedback loop, where sensory percepts, either produced deliberately via rendering through feedback mechanisms or incidentally via transferal through the socket, stimulate mechanoreceptors in the user’s residual limb. f Internal sensory feedback loop, where mechanoreceptors within the muscles of the user’s residual limb transfer information on muscle contraction, fatigue, etc. to the user. Dashed arrows indicate encoded/decoded information; motor and sensory signals that have been encoded by the user’s brain as useful information, or high level commands that have been decoded by the user’s brain to motor signals. . . .	11
1.2	Multifaceted assessment of user performance with myoelectric prosthetic hands. a Psychological assessment: questionnaires quantifying task load, embodiment, and post-study interviews give insight to the psychological effects of new innovations in myoelectric control. b Physical assessment: accuracy metrics, performance metrics on isolated tasks, and performance on contextual activities of daily living give insight into the physical effects of new innovations in myoelectric control.	13
2.1	The proposed robot-enhanced virtual reality training platform (a) in real life, (b) in virtual reality—the virtual hand is mounted below the forearm of the user. Force feedback that would be felt when wearing a prosthetic hand is rendered from the virtual environment to the user’s forearm using an external robot arm.	19

2.2	The OLYMPIC hand attached to the forearm of a user. Annotated: EMG Sensors, Offset Block, Control Electronics, and the OLYMPIC Hand. To be as close as possible to existing direct control prosthetic control methods, only two of the eight EMG electrodes on the Myo Armband are monitored. No other Myo Armband features were used. . . .	22
2.3	Schematic diagram of the fingers and thumb of the OLYMPIC hand, with springs and key dimensions labelled. Left: lateral view of finger i of the OLYMPIC prosthetic hand, (a) relaxed (b) flexed (c) real finger. Right: lateral view of the thumb of the OLYMPIC prosthetic hand, (d) relaxed, (e) flexed, (f) real finger.	23
2.4	The motor torque required to drive to a given encoder position for the thumb and index finger of the OLYMPIC hand. (a) torque required to overcome pre-tensioned springs. (b) friction pattern in the gear driving the thumb. (c) non-linearity caused by the offset spring mounting. (d) static friction overcome as joint begins to move. (e) finger contacts palm.	24
2.5	A comparison between the real and simulated OLYMPIC hand during a full hand closing action. The real OLYMPIC hand (a) open, (b) partially closed, (c) fully closed. The virtual OLYMPIC hand (d) open, (e) partially closed, (f) closed.	25
2.6	The magnitude of the force (top) and torque (bottom) applied by the user to trace a circle at constant speed while attached to the robot arm. Blue - with compensation, red - without compensation. Without compensation the robot arm reaches joint limits and the user is unable to complete the trajectory.	27
2.7	The real (top) and simulated (bottom) experimental setups used in this work to train and evaluate user ability to perform pick and place actions with the prosthetic hand. .	29
2.8	Participant results using the virtual reality prosthetic hand in training trials, then the real prosthetic hand in testing trials. Left: Average Box and Block scores of user groups across 10 training trials and 5 test trials. Right: Average pick-and-place times of YCB objects of user groups across 5 training trials and 5 test trials. Shaded regions represent ± 1 standard deviation. VR - virtual reality group, RE - robot-enhanced group, C - control group.	30
2.9	Mean (standard deviation shown) NASA Task Load Index responses for each participant group after training (Tr) and testing (Te). VR - virtual reality group, RE - robot-enhanced group, C - control group. Top: participant responses for the Box and Blocks Test. Bottom: participant responses for the YCB pick and place task.	31
3.1	The default, grasping, and gesture configurations implemented on the OLYMPIC hand. (a) Relax (default position), (b) Open Palm and (c) Index Finger Point (gestures), (d) Tripod Grasp, (e) Power Grasp, (f) Tool Grasp, and (g) Lateral Pinch (grasps).	37

3.2	Signal processing steps showing key stages of pre-processing, deep learning classification, decision making, and motor control.	38
3.3	Average confusion matrix of the five trained user classifiers making predictions on their respective validation datasets.	39
3.4	Average first attempt control accuracy of users performing target actions with real action feedback over 90 test repetitions, smoothed with a 30 sample moving average. .	40
3.5	The cylindrical space of electromyography (EMG) data sampled at eight locations around the forearm. Left: The circumferential position θ of each of the eight electrodes in the Myo armband. Right: Illustrative cylindrical space that EMG samples lie on, with the I axis corresponding to the intensity of mean absolute value samples, and θ axis corresponding to the circumferential position of the sample around the forearm.	41
3.6	Kernel density estimation in cylindrical data space. Illustrative two-dimensional kernel density estimation plots, darker blue indicates a higher estimated probability, white points indicate observed data. The horizontal axis represents the intensity of observed samples, I , and the vertical axis represents the circumferential position of the sample around the forearm, θ . Left: example of the truncated Gaussian kernel used in the linear dimension. Middle: example of the von Mises kernel used in the wrapped dimension. Right: example generated kernel density estimate from multiple randomly sampled points.	43
3.7	Sampling from a kernel density estimate (KDE) in cylindrical data space. Illustrative example showing sampling from a kernel density estimate. Left: Original KDE and component data. Upper Middle: intensities sampled from the two dimensional kernel making up the KDE. Lower Middle: component assignment probabilities as a uniform distribution. Right: Data resampled from the KDE to obtain a more representative data sample.	44
3.8	Measuring the distance between samples in cylindrical space. The distance between two points, $[I_i, \theta_i]^T$ and $[I_j, \theta_j]^T$, sampled from a cylindrical space with linear dimension I and circumferential dimension θ . Alternative options to calculate the circumferential distance between the points are shown in orange and purple, respectively.	45
3.9	Illustrative example of the computed Wasserstein distance between two distributions in cylindrical data space. The Wasserstein distance is computed from datapoints resampled from two distributions (here coloured blue and red). Black arrows show the direction of point mass correspondences between sampled data from each distribution that produce the optimal transport solution. Left: offset in the linear intensity dimension. Middle: offset in the wrapped circumferential position dimensions. Right: ‘toy’ muscle activity data showing two independent muscles activating, while others remain inactive.	46

3.10	Illustrative example of the discrete control process. At each control step, the Wasserstein distance between the live data and each of the reference data are computed. If the Wasserstein distance falls below a threshold this reference is accepted as the correct motion.	47
3.11	Summary diagram of the controller presented in this work. Electromyography signals were collected from the forearm of the user via surface electrodes, then the underlying distribution producing the observed signals was estimated using kernel density estimation. The Wasserstein distance was computed between the estimated distribution and a set of reference distributions to determine the desired motion of the prosthetic hand.	47
3.12	The OLYMPIC hand with modular powered forearm. Top: forearm connected to an offset attachment block for participants without upper limb difference. Bottom: forearm connected to a custom socket for the participant with upper limb difference.	48
3.13	The minimum Wasserstein distance between reference distributions against number of reference distributions. References are added in descending order of minimum distance to references already in the library, starting with the reference with the greatest average distance to other references. Minimum detection threshold and mean zero distance are shown as dashed lines. Note that mean zero distance is non-zero due to random sampling.	49
3.14	Left: Average confusion matrix across ten participants without upper limb difference normalised across each true label (1: <i>rest</i> , 2: <i>wrist flexion</i> , 3: <i>wrist extension</i> , 4: <i>tripod</i> , 5: <i>supinate hand</i> , and 6: <i>pronate hand</i>). Right: Confusion matrix for the participant with upper limb difference also normalised (1: <i>rest</i> , 2: <i>supinate hand</i> , 3: <i>pronate hand</i> , 4: <i>power grip</i> , 5: <i>thumb opposition</i> , and 6: <i>pinky finger flexion</i>).	50
3.15	Results of the Jebsen-Taylor Hand Function Test for ten participants without upper limb difference and one participant with upper limb difference. ULD: participant with upper limb difference, w/o ULD: participants without upper limb difference. J1: Writing, J2: Simulated page turning, J3: Small objects, J4: Simulated feeding, J5: Stacking checkers, J6: Large, light objects, J7: Large, heavy objects.	52

4.1	Non-invasive closed-loop continuous control achieved with surface electrodes and a haptic feedback armband. (A) A participant operating the OLYMPIC hand with the closed-loop continuous controller. (B) Physical performance evaluations. Isolated control tasks: position matching, force matching. Isolated sensory tasks: object identification. Contextual activities of daily living: Box and Blocks Test, Jebsen-Taylor Hand Function Test. (C) Psychological performance evaluations. Task load and psychological embodiment questionnaires, and post-study interviews. (D) Open-Loop and Closed-Loop conditions. Open-Loop: no feedback is rendered to the user. Closed-Loop: multimodal feedback is rendered to the user with a haptic feedback armband. (E) Discrete Control and Continuous Control conditions. Discrete Control: reference actions are activated with binary signals. Continuous Control: reference actions are activated with modulated signals proportionally and simultaneously.	56
4.2	Conditionally sampling from a kernel density estimate (KDE) in cylindrical data space. Illustrative example showing conditional sampling from a kernel density estimate at the point $\theta = \Theta$. Left: Original KDE and test components, with individual component kernel probabilities along the θ axis shown. Upper Middle: intensities sampled from the truncated Gaussian kernel. Lower Middle: component assignment probabilities as a multinomial distribution computed from the component kernel probabilities at $\theta = \Theta$. Right: KDE resampled at $\theta = \Theta$	59
4.3	Illustrative example of the continuous control process. At each control step, an approximation of the live data is formed by performing a weighted sum of the reference data in the intensity dimension that minimises the Wasserstein distance between the approximate and live data. A gating function is used to prevent antagonistic pairs of reference data from activating simultaneously.	62
4.4	The motion of a the prosthetic hand and its corresponding sensory feedback modes. (A) A finger of the prosthetic hand shown freely closing (lighter, orange) and contacting an object (darker, purple). (B) Corresponding trajectories of the motor position θ and torque τ of the finger. (C) A section view of the corresponding haptic feedback module showing each mode of sensory feedback - tangential position (green), normal displacement (red), and vibration (blue). (D) The tangential position feedback x , representing finger position, and normal displacement feedback z , representing finger force, corresponding to the motor trajectories in (B). (E) Vibration feedback $v_1 - v_5$ of five modules, providing proprioceptive feedback of wrist pronation-supination. . . .	63

4.5	Psychometric properties of normal displacement and tangential position feedback rendered to the upper arm of users. Left: Just noticeable difference (JND) of normal displacement for each module, measured with a nominal displacement of 3.0 mm. Middle: JND of tangential position for each module, measured with a nominal position of 17.5 mm. Right: PSE of tangential position for five modules used simultaneously (note that module 4 suffered an electrical fault and only 2 user results are presented).	65
4.6	Experimental setup for participants without limb difference. Experimental setup for participants without limb difference for stages 1 and 2 (top) and 3 (bottom), in open-loop conditions (left) and closed-loop conditions (right).	67
4.7	Setup of the position matching experiments. Position matching experiments were performed with the prosthesis desk-mounted (left). During training, participants were exposed to explicit visual feedback showing the position of the 5 finger motors and 1 wrist motor of the prosthetic hand in the form of the red bars showing achieved position on the graphical user interface (middle). During testing, the red bars were removed, leaving only the green bars showing target position (right).	68
4.8	Setup of the force matching experiments. Force matching experiments were performed with the prosthesis desk-mounted (left). During training, participants were exposed to explicit visual feedback showing the force applied by the 5 finger motors in the prosthetic hand in the form of the red bars showing achieved force on the graphical user interface (middle). During testing, the red bars were removed, leaving only the green bars showing target force (right).	68
4.9	Setup of the object identification experiments. During training, participants were able to see the hand grasp each object twice. During testing (top), participants wore a blindfold and each object was grasped five times in a random order. The five objects taken from the YCB object and model set used for object identification experiments (middle row): a bleach bottle, a strawberry, a soft brick, a screwdriver, and a tuna can.	69
4.10	Dexterity assessments performed by participants. Top: the Box and Blocks Test: participants must transfer as many blocks as possible from one half of the box to the other in 1 minute. Left: a participant without limb difference completing the Box and Blocks Test. Right: assembled Box and Blocks Test. Bottom: the Jebsen-Taylor Hand Function Test. Left: a participant without limb difference completing the Jebsen-Taylor Hand Function Test. Right: Tasks from the Jebsen-Taylor Hand Function Test, from left to right, top row: (J1) writing, (J2) simulated page turning, (J3) small objects, (J4) simulated feeding. From left to right, bottom row: (J5) stacking checkers, (J6) large, light objects, and (J7) large, heavy objects.	69

4.11 Participant results of isolated control tasks. (A, B, D) Mean absolute error of groups of participants without limb difference (A) and participants with limb difference (D) during training and testing trials of a position matching task with the prosthetic hand, with setup shown (B). Participants were asked to match target positions in sets of single and dual degree of freedom motions, performed with no prior training starting from 1 degree of freedom motions, working to 2 degree of freedom motions, corresponding to the clockwise direction on each plot. Results of paired t -tests at $*p < 0.05$, $**p < 0.01$, and $***p < 0.001$ levels between the OLCC participant group and the CLCC participant group during testing are shown. (C, E, F) Mean absolute error of groups of participants without limb difference (C) and participants with limb difference (F) during training and testing trials of the force matching experiment, with setup shown (E). Participants were asked to match target forces along the two grasping degrees of freedom. Results of paired Mann-Whitney U tests at $**p < 0.01$ level between training and test results of OLCC and CLCC groups (C) are shown as linked asterisks on respective plots. In all plots, error bars show one standard deviation, and paired Mann-Whitney U tests at $*p < 0.05$, $**p < 0.01$, and $***p < 0.001$ levels between individual participants with limb difference and the CLCC participant group during testing are shown as floating asterisks on the plots for the OLCC group (A, D) and individual participants with limb difference (C, E), respectively.	70
---	----

4.12 Participant results of isolated sensory tasks. (A) Object classification accuracy of groups of participants without limb difference. Statistical significance of paired Mann-Whitney U tests shown at $*p < 0.05$ and $**p < 0.01$ levels. (B): Object classification accuracy of individual participants with limb difference, mean and ± 1 standard deviation of the CLCC group results are shown for comparison as a black line and shaded region, respectively. The faded results shown for participant 006 are produced by swapping their predictions for the bleach bottle and soft brick due to consistent misclassification between the two objects. Note: random chance is 0.2. (C) Experimental setup; participants grasped five objects five times in a random order without visual feedback. Objects (clockwise): bleach bottle, strawberry, soft brick, screwdriver, and tuna can. Confusion matrices of participant groups and individual participants with limb difference are shown in Appendix A Fig. A.5 and A.6, respectively.	72
---	----

4.13	Participant results of dexterity assessments. (A - H) Dexterity assessment results of groups of participants without limb difference (A-D) and individual participants with limb difference using the closed-loop continuous controller (E-H) performing tasks from the Jebsen-Taylor Hand Function Test that are static tasks (A, E), manual tasks (B, F), and precision tasks (D, H), and the Box and Blocks Test (C, G). In (E-H), mean and ± 1 standard deviation of the CLCC group results are shown for comparison as a black line and shaded region, respectively. Statistical significance of paired Mann-Whitney U tests shown at $*p < 0.05$ level.	73
4.14	Task load responses of participants. Responses of participants to the NASA-TLX questionnaire after stages 1, 2, and 3 of the study.	74
4.15	Prosthetic embodiment responses of participants before (stage 0) and during (stages 1-3) the study. Responses of participants to the prosthetic embodiment questionnaire statements 1. ‘The prosthesis is my hand’, 6. ‘My body feels complete’, 12. ‘The prosthesis moves the way I want it to move’, and 14. ‘The movement of the prosthesis feels like an actual movement’. Responses to all questions are shown in Appendix A Fig. A.7.	75
5.1	A taxonomy of real and fictional upper limb prostheses. a A taxonomy of real (seen in clinical use, history, or research) and fictional (seen in works of art and fiction) upper limb prostheses, formed by two high-level boundaries, modes of actuation, and targeted action. Targeted actions are categorised into task-specific or either the dominant form of motion (multi-articulating for electro-mechanical, general for body-powered, and holder for passive/static prostheses) or function (gripper for electro-mechanical and body-powered, and holder for passive/static prostheses). Circle area is proportional to number of instances found. b-e Four terminal devices are presented in this work, each in a different branch of the taxonomy, and are the only current examples of real-world task-specific electromechanical prostheses: Hand-Motion, Flicking Device (b), Tool-Motion, Twisting Device (c), Hand-Function, Suction Device (d), and Tool-Function, Cutting Device (e). f The Hydra Prosthesis, which combines body-powered grasping with electromechanical wrist rotation.	85
5.2	The modular base prosthesis used to test each task-specific device. The OLYMPIC hand, the modular test base used to actuate and control each terminal device. Motor interface and modular finger labelled.	90

5.3	Four non-anthropomorphic, task-specific prosthetic terminal devices. a, b , Flicking device: section view of the flicking mechanism (a), initial, drawn, and released positions of the device (b). c, d , Twisting device: exploded view of the gear mechanism used to produce testing motion (a), a screwdriver mounted in the device and the device being used to screw in a cross-head screw (d). e, f , Suction device: section view of the spring-release suction cup mechanism (e), the suction device holding a mobile phone (f). g, h , Cutting device: internal view of the crank and rocker mechanism driving the cutting motion (g), the device cutting a sheet of tissue paper (h).	91
5.4	The design of a grasp-specific non-anthropomorphic prosthesis: the Hydra Prosthetic Hand. a , Key dimensions of the hand, modelled on a human hand. b , Grasping capabilities of the Hydra Hand that mimic those of a human hand, grasping a ball, an articulated chain, and a washer.. c , The finger locking mechanism of the hand. Flexion axes of the distal joints of each finger are misaligned, and locating magnetic features embedded in each finger prevent relative in-plane rotation and translation of laterally adjacent links. d , Schematic diagram of the fingers and joints of the hand. Flexion tendons are shown in red on the palmar side of each finger. Extension elastic cords are shown in blue on the dorsal side of each finger.	99
5.5	Joint space of an individual finger of the Hydra Prosthetic Hand, with joint limits and lines of constant tendon length shown. Lines of constant tendon length are coloured according to the amount of stored elastic potential energy in the elastic extension cord, with lighter showing less energy, and darker showing more energy (normalised per line). The minimum-energy unhindered joint-space trajectory of a finger is shown from rest $(-\frac{\pi}{6}, 0)$ to maximum flexion $(\frac{\pi}{3}, \frac{\pi}{2})$ in red.	102
5.6	Objects used for the YCB Gripper Assessment Benchmark (a) and Soft Object Gripper Benchmarks (b).	103

5.7	Non-anthropomorphic terminal devices improve user task performance. a Performance of participants using the Flicking Device and the control prosthesis on a disc flicking task. Scale diagram of flicked disc location ($\bigcirc$), target disc locations (1 – 7), with corresponding hit rates shown. b Mean task completion time of participants using the Twisting Device and the control prosthesis on a screwing task. Shaded areas show ± 1 standard deviation. c Performance of participants using the Suction Device and the control prosthesis on the stacking checkers task of the JTHFT. Shaded areas show ± 1 standard deviation. d Performance of participants using the Cutting Device and the control prosthesis on a circle cutting task: scatter plot of relative circularity of the cut circle (1.00 indicates a perfect circle) against task completion time, with kernel density estimate plots of circularity and completion time shown adjacent to each axis. Results of (a) paired z -tests, (d) paired two-tailed Mann-Whitney U tests: $*p < 0.05$, $**p < 0.01$, and $***p < 0.001$. † The screwing task was completed by Participant 1 with the assistance of a carer, as it was a bimanual task. ‡ The cutting task is a bimanual task; Participant 1 used their left residual limb (above elbow) to hold and manoeuvre the paper that was cut.	104
5.8	Reduced compensatory motion with non-anthropomorphic terminal devices. a-d , Mean absolute angular deviation θ of participants using the Flicking Device and the control prosthesis on a disc flicking task (a), the Twisting Device and the control prosthesis on a screwing task (b), the Suction Device and the control prosthesis on the stacking checkers task of the JTHFT (c), and the Cutting Device and the control prosthesis on a circle cutting task (d). Results of paired two-tailed Mann-Whitney U tests: $*p < 0.05$, $**p < 0.01$, and $***p < 0.001$ (a-d). e Diagrams illustrating the locations of 6-DOF pose trackers on the body of each participant, and the angular deviation from rest computed at each timestep. f Trackers worn by Participant 1. † The screwing task was completed by Participant 1 with the assistance of a carer, as it was a bimanual task. ‡ The cutting task is a bimanual task; Participant 1 used their left residual limb (above elbow) to hold and manoeuvre the paper that was cut.	105
5.9	Non-anthropomorphic devices reduce task load in users. Raw TLX responses to a mental demand, b physical demand, c perceived performance, and d frustration for each device on their corresponding task. Fl. - flicking disc task, Sc. - screwing task, St. - stacking task, and Cu. - cutting task. All plots show results of paired two-tailed Mann-Whitney U tests: $*p < 0.05$, $**p < 0.01$. † The screwing task was completed by Participant 1 with the assistance of a carer, as it was a bimanual task. ‡ The cutting task is a bimanual task; Participant 1 used their left residual limb (above elbow) to hold and manoeuvre the paper that was cut.	107

5.10 Responses of participants with upper limb difference to the embodiment questionnaire after each task. a Disk flicking task, b screwing task, c the stacking checkers task of the Jebsen Taylor Hand Function Test, and d circle cutting task. Questions were answered on a 7-point Likert scale after completing each task; full list of questions is given in Appendix B Table A.3. † The screwing task was completed by participant 1 with the assistance of a carer, as it was a bimanual task. ‡ The cutting task is a bimanual task; participant 1 used their left residual limb (above elbow) to hold and manoeuvre the paper that was cut. Abbreviations: s/w - somewhat, s. - strongly.	108
5.11 Results of the YCB Gripper Assessment Benchmark. For rigid objects, in each 2×2 square, cells are coloured dark or light according to respective success or failure according to the following criteria: top left if a successful grasp is achieved in the vertical orientation, top right if the object is static for 3 seconds after being grasped from above, bottom left if the object remains held while rotated to horizontal, and bottom right if the object is completely static for 3 seconds after being rotated. This was repeated at an origin point $\mathcal{O}$, and at 1 cm offsets Δx , Δy , and Δz . For articulated objects, there are 20 cells showing attempted grasp success or failure, coloured dark or light accordingly. Each cell is divided according to grasp mode used: precision, cylindrical, and spherical modes are shown in orange, magenta, and blue, respectively.	109
5.12 Results of the Soft Object Gripper Benchmark A. Items of clothing are grasped and dragged 500 mm horizontally, and placement error is measured. Results for single, double, and folded edges are shown. Bars show median result, $\circ$ and $\times$ marks show successful and failed attempts, respectfully.	109
5.13 Results of the Soft Object Gripper Benchmark C: items of clothing are crumpled, then grasped and lifted until contact with the table is completely broken. Lift height required to break contact with the table (of successful grasps) is shown; Bars show median result, $\circ$ and $\times$ marks show lifts that did and did not break contact with the table, respectively. Note that the Hydra Hand failed to grasp the jeans 3/5 times in the crumpled state.	110
5.14 A demonstration of the Hydra Hand on a challenging manipulation task and in use as a prosthetic hand. a Using spherical mode to grasp a bunch of grapes via caging. b Using precision mode to pick a single grape from the bunch. c The Hydra Prosthetic Hand being used to grasp a bottle of water by an end user.	112

A.1	Experimental setup for each participant with limb difference. Experimental setup for each participant with limb difference for stages 1 and 2 (left), and 3 (right). During stages 1 and 2, participants wore only the electrode armband and haptic feedback armband, while the prosthetic hand was desk-mounted. During stage 3, participants also donned the prosthetic hand. Note that participant 001 used an elastic sling to support the prosthesis due to having a short residual limb, and wore the haptic feedback armband on the opposing arm during stage 3 due to space constraints.	145
A.1	(Cont.) Experimental setup for each participant with limb difference. Experimental setup for each participant with limb difference for stages 1 and 2 (left), and 3 (right). During stages 1 and 2, participants wore only the electrode armband and haptic feedback armband, while the prosthetic hand was desk-mounted. During stage 3, participants also donned the prosthetic hand. Note that an elastic belt held by the opposing arm to support the prosthesis was used for participants 007 and 010 due to having a short residual limb, and participant 008 due to having partial paralysis of the right arm and shoulder.	146
A.2	Matching performance experimental results of groups of participants without limb difference. Participants were asked to match target positions in sets of increasing complexity in terms of the number of degrees of freedom required, then were asked to match target forces with each grasping degree of freedom. Left: Position matching performance of single and dual degree of freedom motions, performed with no prior training starting from 1 degree of freedom motions, working to 2 degree of freedom motions in the order shown. Right: Force matching performance of single degree of freedom grasps. Statistical significance of Kolmogorov-Smirnov tests shown at $*p < 0.05$, $**p < 0.01$, and $***p < 0.005$ levels.	147
A.2	(Cont.) Matching performance experimental results of groups of participants without limb difference. Participants were asked to match target positions in sets of increasing complexity in terms of the number of degrees of freedom required, then were asked to match target forces with each grasping degree of freedom. Left: Position matching performance of single and dual degree of freedom motions, performed with no prior training starting from 1 degree of freedom motions, working to 2 degree of freedom motions in the order shown. Right: Force matching performance of single degree of freedom grasps. Statistical significance of Kolmogorov-Smirnov tests shown at $*p < 0.05$, $**p < 0.01$, and $***p < 0.005$ levels.	148

A.3	Matching performance experimental results comparison between the OLCC and CLCC groups. Participants were asked to match target positions in sets of increasing complexity in terms of the number of degrees of freedom required, then were asked to match target forces with each grasping degree of freedom. Left: Position matching performance of single and dual degree of freedom motions, performed with no prior training starting from 1 degree of freedom motions, working to 2 degree of freedom motions in the order shown. Right: Force matching performance of single degree of freedom grasps. Statistical significance of Kolmogorov-Smirnov tests shown at $*p < 0.05$, $**p < 0.01$, and $***p < 0.005$ levels.	148
A.4	Matching performance results of participants with limb difference. Participants were asked to match target positions in sets of increasing complexity in terms of the number of degrees of freedom required, then were asked to match target forces with each grasping degree of freedom. Left: Position matching performance of single and dual degree of freedom motions, performed with no prior training starting from 1 degree of freedom motions, working to 2 degree of freedom motions in the order shown. Right: Force matching performance of single degree of freedom grasps. Note: Participants 001 and 005 only controlled DOF 1 and 2 of the prosthetic hand.	149
A.4	(Cont.) Matching performance results of participants with limb difference. Participants were asked to match target positions in sets of increasing complexity in terms of the number of degrees of freedom required, then were asked to match target forces with each grasping degree of freedom. Left: Position matching performance of single and dual degree of freedom motions, performed with no prior training starting from 1 degree of freedom motions, working to 2 degree of freedom motions in the order shown. Right: Force matching performance of single degree of freedom grasps. Note: Participants 001 and 005 only controlled DOF 1 and 2 of the prosthetic hand.	150
A.4	(Cont.) Matching performance results of participants with limb difference. Participants were asked to match target positions in sets of increasing complexity in terms of the number of degrees of freedom required, then were asked to match target forces with each grasping degree of freedom. Left: Position matching performance of single and dual degree of freedom motions, performed with no prior training starting from 1 degree of freedom motions, working to 2 degree of freedom motions in the order shown. Right: Force matching performance of single degree of freedom grasps. Note: Participants 001 and 005 only controlled DOF 1 and 2 of the prosthetic hand.	151

A.5	Object classification results of groups of participants without limb difference. Confusion matrices of groups of participants without limb difference classifying 5 objects from sensory feedback provided by the haptic feedback armband and incidental (audio) feedback.	152
A.6	Object classification results of participants with limb difference. Confusion matrices of participants with limb difference classifying 5 objects from sensory feedback provided by the haptic feedback armband and incidental (audio) feedback.	153
A.7	Prosthetic embodiment results of groups of participants without limb difference and individual participants with limb difference. Responses of groups of participants without limb difference and individual participants with limb difference to prosthetic embodiment questionnaire statements. Results of paired Mann-Whitney U tests are shown at $*p < 0.05$, $**p < 0.01$, and $***p < 0.001$ levels.	154
A.7	(Cont.) Prosthetic embodiment results of groups of participants without limb difference and individual participants with limb difference. Responses of groups of participants without limb difference and individual participants with limb difference to prosthetic embodiment questionnaire statements. Results of paired Mann-Whitney U tests are shown at $*p < 0.05$, $**p < 0.01$, and $***p < 0.001$ levels.	155
A.7	(Cont.) Prosthetic embodiment results of groups of participants without limb difference and individual participants with limb difference. Responses of groups of participants without limb difference and individual participants with limb difference to prosthetic embodiment questionnaire statements. Results of paired Mann-Whitney U tests are shown at $*p < 0.05$, $**p < 0.01$, and $***p < 0.001$ levels.	156
A.7	(Cont.) Prosthetic embodiment results of groups of participants without limb difference and individual participants with limb difference. Responses of groups of participants without limb difference and individual participants with limb difference to prosthetic embodiment questionnaire statements. Results of paired Mann-Whitney U tests are shown at $*p < 0.05$, $**p < 0.01$, and $***p < 0.001$ levels.	157
A.7	(Cont.) Prosthetic embodiment results of groups of participants without limb difference and individual participants with limb difference. Responses of groups of participants without limb difference and individual participants with limb difference to prosthetic embodiment questionnaire statements. Results of paired Mann-Whitney U tests are shown at $*p < 0.05$, $**p < 0.01$, and $***p < 0.001$ levels.	158
B.1	Worn setup used by participants. Chest, upper arm, and lower arm trackers and socket worn by participant 1 with upper limb difference.	239

B.2	Circles cut by participants for the circle cutting task to test Terminal Device 4. Top: Circles cut by participants using Terminal Device 4. Bottom: Circles cut by participants using the anthropomorphic hand. Each circle is annotated with its relative circularity (blue numeric value in the centre of each circle), target shape (green outline), detected contour (red outline), and participant/attempt (<i>P_A</i> , above each circle).	240
B.3	Responses of participants to all questions of the NASA Task Load Index questionnaire. Raw TLX responses to a mental demand, b physical demand, c temporal demand, d perceived performance, e effort, and f frustration for each device on their corresponding task. All plots show results of paired two-tailed Mann-Whitney U tests: $*p < 0.05$, $**p < 0.01$. † The screwing task was completed by participant 1 with the assistance of a carer, as it was a bimanual task. ‡ The cutting task is a bimanual task; participant 1 used their left residual limb (above elbow) to hold and manoeuvre the paper that was cut.	241

Chapter 1

Introduction

1.1 Motivation

Upper limb difference (ULD), either acquired congenitally or later in life from trauma, is a physical condition that affects over 20 million adults globally [McDonald et al. 2021]. Note that the term physical *condition* is used here rather than *disability*, because many adults with ULD do not view themselves as disabled, particularly those who have congenital ULD. Regardless of terminology — which will be defined later in this chapter — statistically, this group have poorer mental [Østlie et al. 2011b] and physical health [Østlie et al. 2011a], and face functional restrictions in their personal [Johansen et al. 2016] and professional lives [Johansen et al. 2015; Postema et al. 2016].

Prosthetic hands exist to alleviate some of these problems — generally through functional restoration — and myoelectric prostheses, specifically, may well represent the best direction for achieving this goal in most users. Myoelectric prostheses typically use the small electrical signals produced during the contraction of muscles present in the residual limb of a person with upper limb difference as a control input. The process of recording these signals is known as electromyography, and the signals are often referred to as EMG signals. Electromyography is appealing for use in upper limb prostheses, given that the majority of the muscles that control a human hand are located in a person’s forearm. After an individual acquires an upper limb difference at a below elbow level, some of this muscle tissue remains in their residual limb, and is available for myoelectric control. At first glance, this is ideal: residual forearm muscles, that would otherwise control the hand in the absence of an upper limb difference, provide a direct window into the user’s intention. Furthermore, these signals are already separated by their respective muscle groups, dramatically simplifying how user intention is decoded, as opposed to obtaining signals from a source higher along the neural pathway such as in the brain. However, several factors complicate this otherwise ideal scenario: upper limb differences often occur at different levels [Atkins et al. 1996; Giele et al. 2001]; there is extreme heterogeneity of residual muscle tissue from person to person [Gaine et al. 1997]; damage and developmental issues can impair an individual’s ability to activate the muscle tissue [Jones and Davidson 1999]; surgical procedures

such as targeted muscle reinnervation alter EMG signals [Miller et al. 2008]; and other physiological and sensing challenges such as cross-talk between electrodes and user fatigue [Reaz et al. 2006; Ortiz-Catalan et al. 2012; Jiang et al. 2014; Pasquina et al. 2015], all contribute to the far-from-solved myoelectric control problem.

Myoelectric prosthetic hands have been under development since the mid 1900s [Reiter 1948; Battye et al. 1955; Michael and Crawford 1963; Sherman 1964], and fictional prostheses such as Luke Skywalker’s hand in Star Wars [Kershner and Lucas 1980], or even the highly functional hand used by the character Furiosa in the dystopian world of Mad Max: Fury Road [Miller 2015] may lead many to believe that myoelectric prosthetic hands are a solved—or nearly solved—problem. However, even after nearly 80 years, the rejection rate for myoelectric prosthetic hands is staggeringly high, at around 40% — something that has remained unchanged for decades [Malone et al. 1984; Biddiss and Chau 2007a; Salminger et al. 2019; Salminger et al. 2020]. Alongside this, common complaints such as poor functionality and discomfort are as prevalent now as they ever were [Atkins et al. 1996; Gaine et al. 1997; Biddiss and Chau 2007b; Espinosa and Nathan-Roberts 2019; Salminger et al. 2020]. Technological advances made over this time period are not having the widespread positive impact on end-users they are intended to in areas such as user training [Widehammar et al. 2021], additive manufacturing [Kate et al. 2017], and the development of multi-articulating prosthetic hands [Kerver et al. 2023].

While the majority of research is not reaching or benefiting the wider population of adults with ULD, some notable studies and techniques have made strides in improving outcomes for smaller audiences. Invasive methods — those where further surgical procedures are utilised — can provide individuals with cleaner EMG signals via implanted electrodes [Lukyanenko et al. 2021; George et al. 2019; Brinton et al. 2020; Paskett et al. 2021; Ortiz-Catalan et al. 2023] or targeted muscle reinnervation [Kuiken et al. 2004; Miller et al. 2008; Cheesborough et al. 2015], as well as restored sensation via nerve stimulation [George et al. 2019; D’Anna et al. 2019; Clemente et al. 2019; Zollo et al. 2019; Ortiz-Catalan et al. 2023] or nerve reinnervation [Hebert et al. 2014; Marasco et al. 2021], and improved attachment to the body via integration with the user’s skeletal system via osseointegration [Jönsson et al. 2011; Ortiz-Catalan et al. 2023]. However, invasive methods are expensive, often experimental, and the prospect of a surgical procedure to attain incremental gains in functionality render them unpopular with the wider population [Resnik et al. 2019; Salminger et al. 2019]. Furthermore, these methods are only suitable for a small subset of potential end-users, in that the neural pathways and bone structure in individuals with congenital ULD may not have developed to the point where targeted muscle/sensory reinnervation or osseointegration, respectively, would be possible.

It is clear that there is a need for innovation in the field of upper limb prosthetics, with technological advancements that are more applicable to this large, heterogeneous population of adults with individual needs and challenges.

1.2 Preliminaries

1.2.1 Upper Limb Difference

Upper limb difference is a term that refers to a variation in the shape or form of a person's arm and/or hand. This subsection details key causes of upper limb difference, the level (in terms of the location along the arm) at which the upper limb difference is present, and the prosthetic technology available to the person.

Causes of Upper Limb Difference

Upper limb differences have a multitude of causes, which fall into two categories: congenital (from birth), and acquired later in life through amputation. There are many known chemical causes of congenital limb difference [Alexander et al. 2016], with the most well-known being Thalidomide, which led to the infamous Thalidomide Disaster in the late 1950s and early 1960s that was responsible for over 10,000 children being born with limb difference [Vargesson 2015]. Today, smoking, pollutants, and other complex environmental factors continue to lead to congenital limb differences [Czeizel et al. 1994; Alexander et al. 2016], making it unlikely that this cause of limb difference will reduce in prevalence any time soon. Upper limb difference acquired from amputation is also complex. Elective (optional) upper limb amputation is sometimes used as a preventative measure against cancer [Puhaindran et al. 2012] or as treatment for pain after brachial plexus nerve injury [Maldonado et al. 2016]; the former retains a large amount of fully functional muscle tissue, while the latter does not (on account of damage to the nerves controlling this muscle tissue). Unelective (emergency or urgent) upper limb amputation refers to surgical removal of part of the arm or hand in response to a traumatic injury, such as workplace injury, vehicular accident, or major infection during sepsis [McDonald et al. 2021]. The traumatic origin of each unelective surgery mean that there is a large amount of heterogeneity in residual limb condition across patients, which considerably impacts the prosthetic technology that is available to an individual with upper limb difference.

Levels of Upper Limb Difference

Upper limb difference can affect any location along a person's arm or hand. When the upper limb difference is acquired through amputation, the result can be:

- Transcarpal amputation - a partial hand removal (through a carpal bone).
- Wrist disarticulation - the removal of the hand through the wrist joint.
- Transradial amputation - sometimes referred to as a below elbow amputation; the removal of the hand and forearm at a point below the elbow (through the radial and ulnar bones).

- Elbow disarticulation - the removal of the hand and forearm through the elbow joint.
- Transhumeral amputation - sometimes referred to as an above elbow amputation; the removal of the arm at a point between the elbow and shoulder (through the humerus bone).
- Shoulder disarticulation - the removal of the arm through the shoulder joint.
- Forequarter amputation - the removal of the arm above the shoulder itself.

Acquired congenitally, an upper limb difference can be either terminal — affecting the hand itself as well as part of the arm — or intercalary — affecting only part of the arm, and not affecting the hand. Congenital limb difference is also either transverse — affecting all bones in a given region of the arm — or paraxial — affecting only some of the bones in a given region of the arm. While for upper limb differences acquired through amputation some form of internal muscle structure may be retained, this is not the case for many congenital limb differences. For many individuals, a minimal number of muscle groups have developed in the forearm, dramatically reducing the level of sophistication achievable with a myoelectric controller.

For a prosthetic hand designer, each level of upper limb difference brings a new set of challenges. A higher upper limb difference affords room for batteries, actuators, and the prosthetic hand itself, but control requirements become harder to satisfy as more joints must be emulated, and control of these joints becomes more difficult as fewer muscle groups in the arm are available to provide control inputs. A lower level upper limb difference, meanwhile, provides access to far more control inputs, while requiring less joints to be emulated, but far less space is available to house the components required for an actuated prosthesis.

Available Prosthetic Technology

The prosthetic technology available to someone with upper limb difference varies dramatically, not only depending on their limb difference [Trent et al. 2019; Salminger et al. 2020], but also their socioeconomic background [Biddiss et al. 2011]. Available upper limb prostheses fall into one of three categories: passive/static, body-powered, and electromechanical.

Passive/static devices are favoured when a robust, simple, and cost-effective solution is required; cosmetic prostheses are the most common form of prosthesis in this category, but passive/static devices that are task specific have existed for over a century, allowing their user to perform tasks that would otherwise be difficult or impractical. Examples of these are tool-based prostheses such as a hammer hand [Blackrock Special Hospital 1921], or sport prostheses such as the Freestyle Swimming Device (TRS; USA) and the Koalaa Joanie (Koalaa; UK) tennis prosthesis. For upper limb differences at the partial hand level, where space for components is minimal, passive devices are most common [Trent et al. 2019].

Body-powered prostheses utilise redundancy in the user’s shoulder to generate a single mechanical input for a prosthetic terminal device, typically a gripper. The most common design of body-powered prostheses is the split-hook design, which has existed since the early 1910s [Dorrance 1912], however the earliest recorded body-powered prosthesis dates back to 1818 [Zuo and Olson 2014]. Modern split-hook prostheses are nearly identical to the original, and offer a light-weight, robust solution at a relatively low cost [Trent et al. 2019]. These prostheses, however, are restricted to producing single degree of freedom (DOF) motion, and are therefore limited in terms of the actions they can perform, and the reliance on proximal body motion to operate the prosthesis has been shown to increase certain aspects of compensatory body motion [Engdahl et al. 2022] — a known cause of musculoskeletal pain. For those with a reduced capacity to produce control inputs for an electromechanical prosthesis, body-powered prostheses are a lighter, more robust, and cheaper alternative [Trent et al. 2019].

Electromechanical prostheses use powered actuators to produce motion of a prosthetic terminal device. These prostheses make use of control inputs from the user’s body, which can come from a range of sources, including: ultrasound images of muscles [Dhawan et al. 2019a], mechanical vibrations produced during muscle contraction [Wilson and Vaidyanathan 2017], brain electrical activity produced when thinking about an action [Murguialday et al. 2007], and the small electrical signals produced by muscles during contraction [Battye et al. 1955]. The latter, recorded in a process known as electromyography, is by far the most common in the control of upper limb prostheses (known as myoelectric control) [Kumar et al. 2019; Geethanjali 2016]. Given that the majority of hand motion is produced by muscles located in the forearm, if a person’s upper limb difference is at below elbow level then myoelectric control using electrodes placed on the forearm is a non-invasive way of obtaining multiple restorative control inputs. However, electromechanical prostheses bring a series of drawbacks — they are comparatively heavier, much more expensive, and more fragile than body-powered or passive/static prostheses [Trent et al. 2019]. Furthermore, advanced, multi-degree of freedom control is only available to users with enough functional muscle groups in their residual limb, reducing the utility of these prostheses for those with upper limb differences acquired congenitally, from traumatic injury, who have nerve damage, or at a higher level along the arm. Given their capacity to utilise multiple actuators and control inputs, myoelectric prostheses have the potential to offer sophisticated functional restoration to their users; myoelectric control remains an active area of research.

1.2.2 Myoelectric Control

Muscle activity was first considered as a control input for prosthetic hands in the late 1940s and early 1950s [Reiter 1948; Battye et al. 1955], predating even the transistor. In the decades since, more advanced hardware and electronics have increased the myoelectric control capacity of a prosthetic hand to enable potentially multiple degrees of freedom to be controlled simultaneously given an appropriate control algorithm. However, for the many reasons mentioned previously in Section 1.1, developing

myoelectric control algorithms that are robust, intuitive, and easy to calibrate is non-trivial. The remainder of this subsection will outline three key types of myoelectric control along with the challenges associated with each type, before briefly summarising commonly seen output devices for myoelectric control (i.e. the design of myoelectric prosthetic hands).

Traditional Myoelectric Control

Historically, myoelectric control methods relied on analogue electronic circuits to output simple control commands. Traditional control methods are those that perform simple thresholding and proportional control. In most cases, two electrodes are used; one placed above the bulk muscle of the anterior forearm, and the other above the bulk muscle of the posterior forearm. Raw myoelectric signals are zero-mean, with a Nyquist frequency of approximately 1000 Hz [Boxtel et al. 1998]. For most purposes, these raw signals $s(t)$ are first rectified and smoothed by some window function $w(t)$ with width t_W to produce a muscle activity ‘intensity’ signal $i(t)$, either by an analogue circuit:

$$i(t) = \int_{t-t_W}^t |s(\tau)| w(t - \tau) d\tau, \quad (1.1)$$

or after digital sampling at rate f has taken place, giving an intensity at sample k of

$$i(k) = \sum_{j=k-W}^k |s(j)| w(k - j), \quad (1.2)$$

where $W = t_W f$, the number of samples in window t_W .

The simplest form of control is on/off control, described in [Sherman 1964]. Given incoming muscle activity signals from these two electrodes $i_1(t)$ and $i_2(t)$, a motor is commanded to its maximum torque $\tau_{\max}$ via monitoring when the differential signal $i_1(t) - i_2(t)$ rises above a threshold $i_{\text{threshold}}$:

$$\tau_{\text{cmd}}(t) = \begin{cases} \tau_{\max} & i_1(t) - i_2(t) > i_{\text{threshold}} \\ -\tau_{\max} & i_2(t) - i_1(t) > i_{\text{threshold}} \\ 0 & \text{otherwise.} \end{cases} \quad (1.3)$$

This can be extended to allow a user to control the torque according to the strength of their muscle contraction, in what is known as ‘proportional control’. Described in [Bottomley 1965], the commanded torque is proportional to the differential signal from the two electrodes, scaled by a constant

of proportionality K_τ :

$$\tau_{\text{cmd}}(t) = \begin{cases} K_\tau \tau_{\text{max}}(i_1(t) - i_2(t) - i_{\text{threshold}}) & i_1(t) - i_2(t) > i_{\text{threshold}} \\ -K_\tau \tau_{\text{max}}(i_2(t) - i_1(t) - i_{\text{threshold}}) & i_2(t) - i_1(t) > i_{\text{threshold}} \\ 0 & \text{otherwise.} \end{cases} \quad (1.4)$$

Further variants of traditional control exist, for example: using multiple intensity thresholds to discretise the commanded torque to set levels; allowing the prosthesis to switch modes according to temporal thresholds to identify rapidly pulsed contractions or co-contraction of antagonistic muscle pairs [Heerschoep et al. 2020a]. However, for single DOF prostheses such as the commercially available Greifer Hand (Ottobock; Germany) small variations on the controllers outlined in (1.3) and (1.4) are favoured, due to the computational simplicity and robustness of traditional controllers. In light of the fact that traditional myoelectric controllers have deeply integrated into widely available commercial myoelectric prostheses for many years, Chapter 2 investigates how user training with traditional myoelectric controllers can be improved, seeking to maximise user performance and foster realistic user expectations of their prosthesis. Furthermore, Chapter 5 investigates how the design of the controlled prosthesis can maximise performance, and four devices are developed to perform the actions of flicking, twisting a screwdriver, picking and placing small flat objects, and cutting paper, respectively, which utilise variations on traditional control methods to robustly perform each single-DOF action.

Discrete Myoelectric Control

A discrete myoelectric controller refers to any controller that moves a prosthesis between fixed positions (these could be grasps or gestures). Indeed, traditional on/off control is a basic form of discrete control with three classes (open hand, stationary, close hand) that are separated by two thresholds, however, in this thesis we will define a discrete controller to have an arbitrary number of classes. A discrete controller is a classifier: based on an input of multi-channel muscle activity data from N electrodes, $\mathbf{s}(k) \in \mathbb{R}^N$, the controller outputs a predicted action for the prosthesis $\hat{\mathbf{a}}(k)$. Generally, a classifier can be written as a function $\mathbf{f}(\cdot)$ of muscle activity $\mathbf{s}(k)$ and a set of trained parameters ϕ , that outputs predicted action $\hat{\mathbf{a}}$ from a set of R reference actions:

$$\hat{\mathbf{a}}(k+1) = \mathbf{f}(\mathbf{s}(k); \phi) \quad \hat{\mathbf{a}} \in [\mathbf{a}_1, \mathbf{a}_2, \dots, \mathbf{a}_R], \quad (1.5)$$

where each action, $\mathbf{a} \in \mathbb{R}^J$, commands J actively controlled joints of the prosthesis. The function (or set of functions) used to perform the classification step has been the topic of decades of research, starting with linear methods [Finley and Wirta 1967] before turning towards more complex methods such as neural networks in the early 1990s [Kelly et al. 1990]. To date, the commercially favoured

method is linear discriminant analysis, which originated in the 1980s [Almström et al. 1981; Saridis and Gootee 1982].

Importantly, calibrating/training a discrete controller requires user data. The parameters ϕ of a discrete controller can be updated according to some cost function $C(f(\cdot; \phi), S, A)$ and a set of known reference muscle activity data-action label pairs $\{S, A\}$. The parameters of the discrete controller can then be chosen to minimise this cost function:

$$\phi = \underset{\phi}{\operatorname{argmin}}(C(f(\cdot; \phi), S, A)). \quad (1.6)$$

When a large number of parameters are required for successful classification, a large amount of user training data and specialised computers are required to train the discrete controller. Given the heterogeneity in residual limb condition across adults with upper limb differences and the day-to-day differences in muscle activity data brought on by donning and doffing the prosthesis, myoelectric controllers are typically user-specific, and therefore the burden of collecting calibration data is typically passed on to the user. Several methods have been employed to reduce this burden. At one extreme, very large models have been trained to perform classification from muscle activity data in a way that generalises across multiple users [Rahimian et al. 2021]. However, these models are extremely large, and are unsuitable for use on a myoelectric prosthesis which has limited computational power and battery duration. At the other extreme, notable works have taken steps to pre-define features of muscle activity that are important for classification (as opposed to the discrete controller learning these entirely during training from raw EMG data) [Hudgins et al. 1993; Reaz et al. 2006]. The drawback of such methods are that such features are somewhat prescriptive and heuristic, and may limit discrete control performance. In Chapter 3, methods to reduce user burden by improving the computational power of prosthetic hands and minimising the required data for discrete control are investigated.

Continuous Myoelectric Control

Continuous myoelectric control is the continuous mapping from muscle activity data to the action that a prosthetic hand performs:

$$\hat{\mathbf{a}}(k+1) = \mathbf{f}(\mathbf{s}(k); \phi) \quad \hat{\mathbf{a}} \in \mathbb{R}^J. \quad (1.7)$$

Here, the action is a continuous vector of commands for J joints of the prosthetic hand. In the ideal scenario, muscle activity signals are linear time-invariant [Chowdhury et al. 2013], meaning all information is captured by the current sample of muscle activity. Indeed, the majority of continuous controllers in literature use some sort of linear method to achieve continuous control [Hahne et al. 2014; Hahne et al. 2018; Lukyanenko et al. 2021]. However, in practice, this may not be the case, and some works include a window of previous muscle activity samples and sometimes a secondary window

of previous actions as inputs to the continuous control model [Xiloyannis et al. 2017]:

$$\hat{\mathbf{a}}(k+1) = \mathbf{f}(\mathbf{s}_{k-W_1:k}, \mathbf{a}_{k-W_2:k}; \phi) \quad \hat{\mathbf{a}} \in \mathbb{R}^J, \quad (1.8)$$

where W_1 and W_2 are the number of samples in the muscle activity and action windows, respectively. Several works have applied non-linear models of varying levels of complexity to predicting a set of joint angles based on muscle activity data [Xiloyannis et al. 2017; Ameri et al. 2019; Betthausen et al. 2020], however none have been successfully implemented on a prosthetic hand, and training data requirements are often too large to be practical for routine calibration by a prosthetic hand user. Moreover, continuously controlling a set of joints of a prosthetic hand requires constant visual attention from the user. Methods to reduce this visual attention with sensory feedback may be vital to making continuous control a viable myoelectric control method. In Chapter 4, a continuous control method is introduced along with a sensory feedback armband, and both are evaluated physically and psychologically with a large number of end users.

Output Devices for Myoelectric Control

The device that is controlled by the myoelectric controller is as important as the controller itself, yet is often overlooked or developed in isolation. The device — a myoelectric prosthesis — exists to convert myoelectric control outputs to real-world actions. Even with an ideal, extremely sophisticated myoelectric controller, achieving the desired control output mechanically is a challenge in itself. Existing myoelectric prostheses fall into two categories: hand-function and hand-motion.

Hand-function myoelectric prostheses replicate the human hand function of grasping, aiming to perform robust grasps that are useful for simple myoelectric controllers. These prostheses are often two-fingered grippers, with the commercially available Greifer Hand (Ottobock; Germany), anthropomorphic grippers, such as the Hannes Hand [Laffranchi et al. 2020], or occasionally multi-fingered grippers, such as the Finch prosthetic arm [Yoshikawa et al. 2023]. While robotic grippers are subject to evaluation with benchmarks such as the YCB Gripper Assessment Benchmark [Calli et al. 2015] and Soft Object Gripper Benchmarks [Clark et al. 2023], prosthetic grippers are evaluated by end-user metrics such as the Box and Blocks Test [Trombly and Scott 1983] and the Clothespin Relocation Test [Hussaini and Kyberd 2017].

Hand-motion myoelectric prostheses, also known as multi-articulating myoelectric prostheses, attempt to recreate as much of human motion as possible. Within the profile of a human hand and forearm and approximate weight restrictions, these hands are generally restricted to around 7 actuators; 5 of these are dedicated to finger flexion, 1 is often used for secondary thumb rotation, and 1 for wrist pronation/supination. Examples of such myoelectric hands are the Southampton Hand [Kyberd and Chappell 1994], the OLYMPIC hand [Liow et al. 2020] (used in this thesis), and commercial hands

such as the Bebionic Hand (Ottobock; Germany) and the iLimb series of hands (Össur; Iceland). Recent literature findings show that multi-articulating prostheses do not lead to more regular use, and that the majority of myoelectric hand use is non-prehensile [Spiers et al. 2021]. This raises questions as to whether the research attention that imitating human hand motion has received for many years is well deserved. In Chapter 5, these categories of upper limb prostheses are investigated and expanded upon, and multiple prosthetic devices are developed.

1.2.3 Myoelectric Control as a Human-in-the-Loop System

Myoelectric Control System Overview

The classes of myoelectric control algorithms and output devices introduced so far are all small parts of a complex, human-in-the-loop system. Summarised in Fig. 1.1, several key sub-systems exist within myoelectric control, including the user’s internal control loop, the conventional myoelectric control system, and external and internal sensory feedback loops. Note that this diagram is a general overview, and variations exist, for example, in terms of sensory information being included in myoelectric control [Krasoulis et al. 2017; Ghazaei et al. 2017], and rendering alternative sources of feedback to the user [Tchimino et al. 2023; Gasparic et al. 2023].

The user’s internal control loop (see Fig. 1.1 a) governs how the user responds to perceived sensory information combined with prior knowledge from training and contextual information about the task they are performing to inform their decision on which action to perform with the prosthesis. This action is then executed by the user via their internal control model, which determines how they must control their own body to elicit the correct response by the prosthesis. The user’s internal control loop changes subject to all other aspects of myoelectric control: sensory feedback mechanisms will provide richer sensory information as an input, training in specific environments provides meaningful prior knowledge, myoelectric control algorithms with low accuracy will poorly impact a user’s internal control model, and a prosthetic end effector which lacks functionality will require compensation by the user’s internal decision model as to how it is used.

The process of obtaining EMG signals from the user’s residual limb is shown in Fig. 1.1 b. As mentioned previously, a range of factors influence the quality of these signals, such as fatigue, skin-electrode contact, and any developmental deviation/damage to the nerves producing the motor signals that activate the muscles. Closely related to this is the user’s internal sensory feedback loop, shown in Fig. 1.1 f, which relays proprioceptive information from the muscles in the user’s residual limb back to the user. The state of both of these subsystems has a large impact on myoelectric control; robustly obtaining EMG signals is critical in achieving high accuracy with a myoelectric control algorithm, and internal feedback from the muscle groups in their residual limb allows a user to repeatably activate desired muscle groups and produce useful EMG signals, and adjust these contractions if the myoelectric

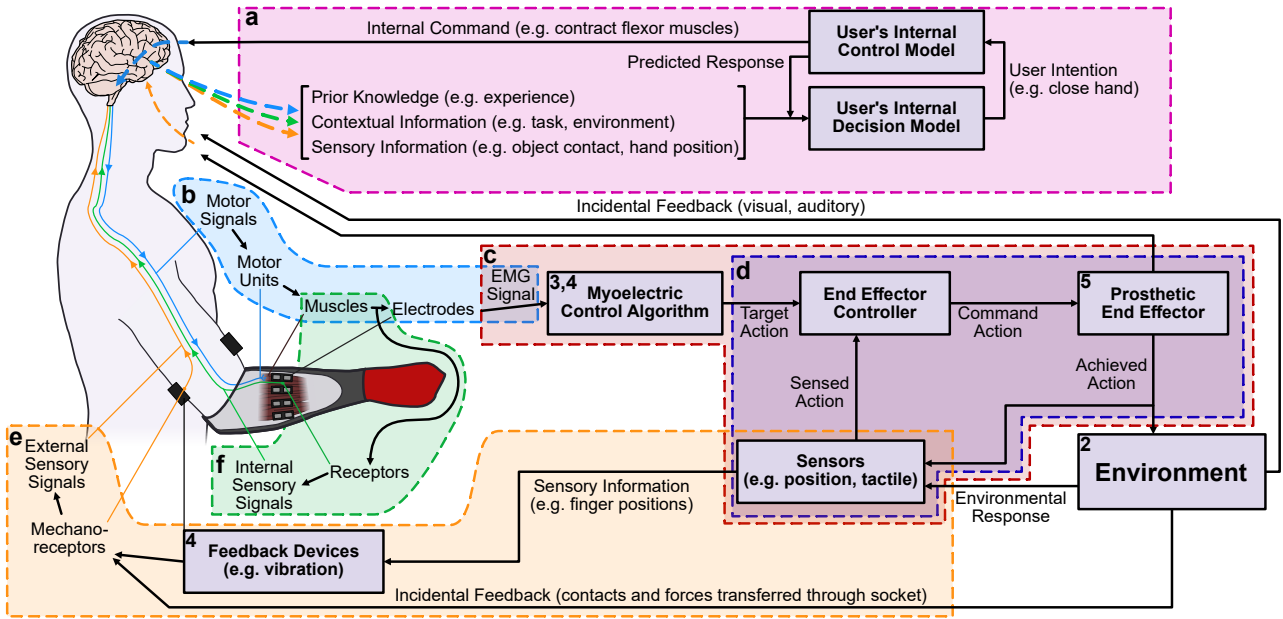


Figure 1.1: Human-in-the-loop control of myoelectric prostheses, blocks are labelled with the chapters in which developments are made. **a** The user's internal control loop, where prior knowledge, contextual information, sensory information, and the predicted response of the prosthesis are inputs to produce a user intention, and consequently an internal command for the muscles of the user's residual limb. **b** The process of motor signals from the user's brain producing recorded EMG signals. **c** The conventional myoelectric control system; a myoelectric control algorithm produces a command action for the prosthetic end effector, which is executed in the environment. **d** Low-level control loop, consisting of the low-level controller of the end effector of the prosthesis, and any sensors such as motor encoders that close this loop. **e** External sensory feedback loop, where sensory percepts, either produced deliberately via rendering through feedback mechanisms or incidentally via transferal through the socket, stimulate mechanoreceptors in the user's residual limb. **f** Internal sensory feedback loop, where mechanoreceptors within the muscles of the user's residual limb transfer information on muscle contraction, fatigue, etc. to the user. Dashed arrows indicate encoded/decoded information; motor and sensory signals that have been encoded by the user's brain as useful information, or high level commands that have been decoded by the user's brain to motor signals.

controller is not functioning in alignment with their internal control model.

The conventional myoelectric control system, shown in Fig. 1.1 c, contains the myoelectric control algorithm and the prosthetic end effector (including the controller's low-level control loop, shown in Fig. 1.1 d). In this subsystem, the myoelectric control algorithm produces a target action for the end effector to perform, and the low-level control loop uses low level control methods such as proportional-integral-derivative control to execute the target action on the prosthesis, with onboard sensors relaying aspects of the state of the prosthesis and its interaction with the environment to the low level controller. Some commercially available prosthetic hands such as the i-Limb (Ossür; Iceland) lack key low level control elements such as position and force sensing, meaning they are unsuitable for use with more sophisticated myoelectric control algorithms such as continuous control. As well as the low level control capabilities of the prosthesis, it is important to consider the mechanical design of the end effector in the development of any myoelectric control algorithm to ensure that any target action from the user can truly be executed, and the end effector fulfils the user's functionality requirements

and expectations.

Finally, the external sensory feedback loop is shown in Fig. 1.1 e, which contains sensory feedback percepts that are detected by mechanoreceptors in the user’s residual limb. The percepts can either be rendered by feedback devices to convey sensed information about a user’s prosthesis, or they can be incidental; the contacts and forces that are transferred from the prosthesis through the socket connection with the user’s residual limb. External sensory feedback is a rich source of information that inputs to the user’s internal decision model, and is often used to restore lost tactile and proprioceptive information from a user’s limb, which is known to play a crucial role in dexterity [Johansson and Flanagan 2009; Sobinov and Bensmaia 2021], however, the rendering of such information first depends on the sensors present in the prosthetic end effector itself. Furthermore, the utility of external sensory feedback in myoelectric control depends on how the prosthetic end effector can be operated in response to feedback, both in terms of the user’s internal decision and control models, and the end effector itself.

It is clear that, in order to maximise the impact of research, myoelectric prosthetic hand control should be investigated as a complete system, without isolating any one subsystem. As an analogy, consider the development of a perfectly engineered fighter jet; without many hours of training, a pilot will find the fighter jet impossible (and dangerous) to fly. Similarly, the development of next-generation myoelectric control algorithms is necessary, but not sufficient: targeted training environments are required to allow a user to develop their internal decision and control models in order for the control algorithm to see any real utility when implemented in a myoelectric prosthetic hand. This thesis addresses this by presenting contributions to multiple aspects of myoelectric control across chapters 2-5 (labelled on Fig. 1.1), culminating in a human-centred, multifaceted investigation into how myoelectric prosthetic hand control can be improved.

Multifaceted Evaluation

With such a complex system it is difficult to evaluate the effects of individual changes with purely conventional metrics such as user performance on standardised tests. It is important to take a multifaceted approach; seeking to understand both the physical and psychological effects of an individual change to the system. This is illustrated in Fig. 1.2, which summarises the physical and psychological assessment methods used in this thesis.

For example, the effect of continuous control versus discrete control may be predominantly non-task-performance related — possibly manifesting in a change in the user’s internal control model. An internal change such as this is challenging to assess, and some works in literature have used questionnaires to assess concepts such as task load, psychological embodiment, and agency [Marasco et al. 2018; Caserta et al. 2022; Parr et al. 2023], or have explored features of eye gaze as an observable proxy for a user’s internal control and decision models [Marasco et al. 2021; Cheng et al. 2022; Kyberd et al. 2023]. In the studies documented in this thesis, post-study interviews and questionnaires are

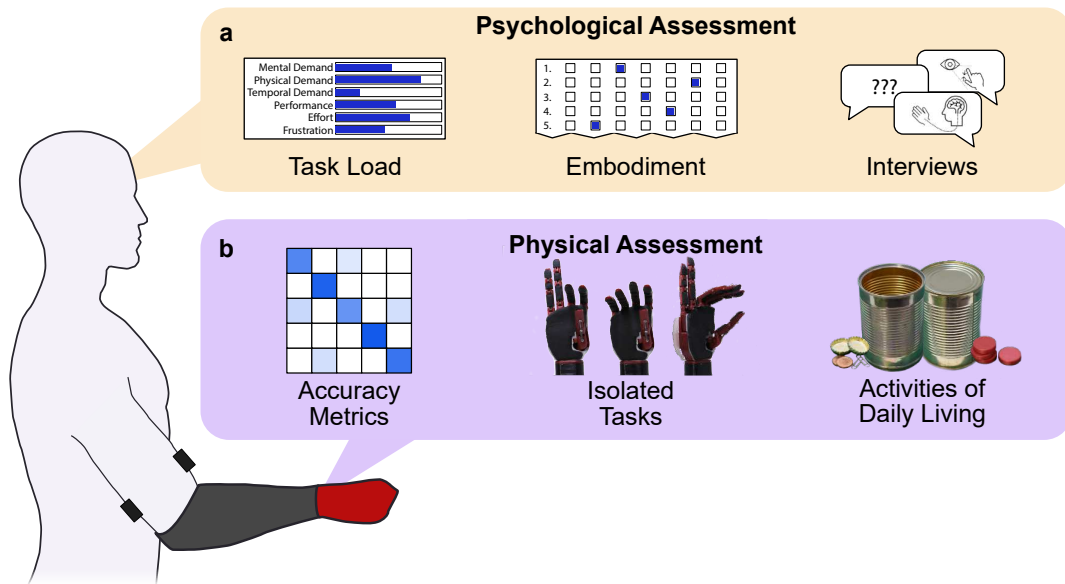


Figure 1.2: Multifaceted assessment of user performance with myoelectric prosthetic hands. **a** Psychological assessment: questionnaires quantifying task load, embodiment, and post-study interviews give insight to the psychological effects of new innovations in myoelectric control. **b** Physical assessment: accuracy metrics, performance metrics on isolated tasks, and performance on contextual activities of daily living give insight into the physical effects of new innovations in myoelectric control.

utilised (shown in Fig. 1.2 a), due to the simplicity and ease by which they are conducted, and because they produce a rich data source that is a direct window into the user’s psychological state after using a prosthesis.

To evaluate the physical effect of a change to the myoelectric control system, a further choice must be made of the combination of assessment tools and tasks on which to evaluate physical user performance. It is sometimes the case, in literature, that a new myoelectric control method is evaluated only on accuracy metrics, such as action classification accuracy [Rahimian et al. 2021] or predicted control position error [Xiloyannis et al. 2017], without actually testing the control method on a real prosthesis. In this thesis, to more completely evaluate each presented contribution, a range of physical assessments are performed (shown in Fig. 1.2 b), including accuracy metrics, but with a focus on specific isolated tasks, where appropriate, and contextual activities of daily living with real end-users.

In summary, there are many overlapping subsystems existing within myoelectric control, and it is clear that a multifaceted approach is needed in order to evaluate and gain a deeper understand the effect of any development or controlled change. A combination of physical and psychological evaluation techniques are needed to provide a more complete picture of a user and their prosthesis, with direct user feedback providing a rich source of information that is often overlooked.

1.2.4 Terminology

The terminology surrounding physical disability is ever changing and continually evolves as our understanding and social attitudes change over time. Terms and phrases that were commonplace even

10 years ago can find themselves inappropriate or unsuitable for use in modern research, and this is particularly present in the field of upper limb prosthetics. Here, I will outline and justify key terminology to be used in this thesis and highlight terms and phrases that are to be avoided when discussing such research, based on the National Center on Disability and Journalism guidelines¹ and feedback from charities and participants that have been involved in my research.

Disability - a person is not defined by their disability. It is preferable to use phrases such as ‘a person with a disability’, rather than a ‘disabled person’. Similar rules apply to persons who have had an amputation (avoiding the term ‘amputee’), and persons with limb difference (avoiding the phrase ‘limb different person’).

Limb Difference - a person with limb difference may not view themselves as having ‘lost’ part of their limb. It is preferable to refer to this as ‘limb difference’, as opposed to limb ‘loss’, ‘deficiency’, ‘reduction’, or otherwise.

Congenital Limb Difference - a person who was born with a limb difference may not view their limb difference negatively. Avoid using terms that have negative connotations such as ‘birth defect’, ‘abnormality’, or otherwise.

Acquired Limb Difference - ‘acquired’ is a suitable neutral word to mean that the person has ‘gained’ a limb difference, and is agnostic to the cause.

With and Without Limb Difference - in the context of research into limb difference, it is preferable use the phrase ‘someone without limb difference’, which is neutral, as opposed to terms such as ‘able-bodied’, ‘healthy’, or ‘non-disabled’, which negatively portray those with limb difference.

End-User - this is a neutral word to identify participants who have the capacity to use myoelectric prosthetic hand technology in their daily life.

Terminal Devices - a ‘terminal device’ is the end effector of a prosthesis. This term is particularly important when considering non-anthropomorphic prostheses — some prostheses may not take the form or function of a human hand, and therefore it may not be suitable to refer to them as a ‘prosthetic hand’.

Prosthetic - ‘prosthetic’ is an adjective used to describe an artificial body part, e.g. a ‘prosthetic hand’. It is not a standalone word, although it is often used as a shortening of the phrase ‘prosthetic hand’ by practitioners and end-users — in research this kind of shortening is to be avoided.

Prosthesis - a ‘prosthesis’ is the artificial body part itself, and is singular. The plural term is ‘prostheses’. For example: ‘I have developed a new prosthesis, based on my experience working with existing prostheses’.

Myoelectric - a ‘myoelectric’ prosthesis is one that uses the small electrical signals produced by the user contracting their muscles (also known as electromyographic signals or EMG signals) as a control input.

¹<https://ncdj.org/style-guide/>

1.3 Publications

The work described in this thesis resulted in the following publications:

- **Digby Chappell**, Honn Wee Son, Angus B. Clark, Zeyu Yang, Fernando Bello, Petar Kormushev, and Nicolas Rojas (Apr. 2022a). “Virtual Reality Pre-Prosthetic Hand Training with Physics Simulation and Robotic Force Interaction”. In: *IEEE Robotics and Automation Letters* 7.2, pp. 4550–4557. [Chappell et al. 2022a].
Video: <https://www.youtube.com/watch?v=beY-pm6CNCM>
- **Digby Chappell**, Zeyu Yang, Honn Wee Son, Fernando Bello, Petar Kormushev, and Nicolas Rojas (July 2022b). “Towards Instant Calibration in Myoelectric Prosthetic Hands: A Highly Data-Efficient Controller Based on the Wasserstein Distance”. In: *IEEE International Conference on Rehabilitation Robotics (ICORR)*. Rotterdam: IEEE, pp. 1–6. [Chappell et al. 2022b].
Video: <https://www.youtube.com/watch?v=AWtHQU4buZI>
- Zeyu Yang, Angus B. Clark, **Digby Chappell**, and Nicolas Rojas (May 2022). “Instinctive Real-time sEMG-based Control of Prosthetic Hand with Reduced Data Acquisition and Embedded Deep Learning Training”. In: *2022 International Conference on Robotics and Automation (ICRA)*. IEEE, pp. 5666–5672. [Yang et al. 2022].
Video: https://www.youtube.com/watch?v=fXIlpW6o_YA
- Alexandre Berkovic, Colin Laganier, **Digby Chappell**, Thrishantha Nanayakkara, Petar Kormushev, Fernando Bello, and Nicolas Rojas (May 2022). “A Multi-Modal Haptic Armband for Finger-Level Sensory Feedback from a Prosthetic Hand”. In: *Haptics: Science, Technology, Applications, EuroHaptics*. Hamburg: Springer, pp. 138–146. [Berkovic et al. 2022].
Video: <https://webcast.tuhh.de/Mediasite/Play/bdcfa56e8f1c4593a4690fd58b644c2d1d>
- **Digby Chappell**, Fernando Bello, Petar Kormushev, and Nicolas Rojas (Sept. 2023). “The Hydra Hand: A Mode-Switching Underactuated Gripper with Precision and Power Grasping Modes”. In: *IEEE Robotics and Automation Letters* 8.11, pp. 7599–7606. [Chappell et al. 2023].
Video: <https://www.youtube.com/watch?v=upLHX3P0im0>
- **Digby Chappell**, Zeyu Yang, Angus B. Clark, Alexandre Berkovic, Colin Laganier, Weston Baxter, Fernando Bello, Petar Kormushev, and Nicolas Rojas (2024b). “Combining multimodal feedback with continuous control improves performance and psychological embodiment in prosthetic hand users”. In: *Scientific Reports (Under Review)*. [Chappell et al. 2024b].
Video: <https://www.youtube.com/watch?v=jsHebMJFOWQ>

- **Digby Chappell**, Barry Mulvey, Shehara Perera, Fernando Bello, Petar Kormushev, and Nicolas Rojas (2024a). “Beyond Humanoid Prosthetic Hands: Modular Terminal Devices That Improve User Performance”. In: *IEEE Transactions on Medical Robotics and Bionics (Under Review)*. [Chappell et al. 2024a].

Video: <https://www.youtube.com/watch?v=845b8045cr8>

1.4 Thesis Structure

The remainder of this thesis is structured as follows:

Chapter 2 investigates how user ability with traditional myoelectric controllers can be improved with more realistic training environments. Specifically, the time period prior to a user receiving their prosthesis is targeted, and a robot-enhanced virtual reality training platform is presented and evaluated in terms of task performance and perceived task load by users.

Chapter 3 investigates how advanced discrete myoelectric controllers can be developed that are suitable for implementation on real prosthetic hands. Two discrete controllers are presented that are entirely personalised to the user, and rely on a relatively small amount of data, the latter of which requires a single snapshot of user data per action to perform.

Chapter 4 introduces a method of achieving closed-loop continuous myoelectric control, whereby multiple degrees of freedom of a prosthetic hand can be controlled simultaneously and proportionally, with a haptic feedback armband closing the feedback loop between the user and their prosthesis by providing proprioceptive feedback from the hand. The performance of the controller is tested extensively in terms of physical aspects of performance and the psychological aspects of performance by groups of participants without ULD and 10 participants with ULD.

Chapter 5 explores the design of the myoelectric prosthesis itself, and whether superior performance can be achieved with prostheses that differ from traditional anthropomorphic designs. A framework for the design of non-anthropomorphic prosthetic hands is presented, and the development and evaluation of four modular terminal devices that fit onto an existing myoelectric prosthesis are detailed. Finally, the design of a non-anthropomorphic hybrid body-powered-myoelectric prosthetic hand is presented and its ability to grasp a range of objects is evaluated.

Chapter 6 concludes the thesis with a discussion of the research presented and suggestions for future work.

Chapter 2

Improving User Ability with Traditional Controllers

This chapter is based on the work presented in:

Digby Chappell, Honn Wee Son, Angus B. Clark, Zeyu Yang, Fernando Bello, Petar Kormushev, and Nicolas Rojas (Apr. 2022a). “Virtual Reality Pre-Prosthetic Hand Training with Physics Simulation and Robotic Force Interaction”. In: *IEEE Robotics and Automation Letters* 7.2, pp. 4550–4557

Traditional myoelectric control algorithms are simple and robust, actuating a small number of required degrees of freedom to achieve tasks. Although these methods have been in use for decades, the techniques to train patients to control prostheses in this way and the environments they are trained in are rudimentary at best. An area that receives little attention is the preprosthetic training phase; the period of time prior to a patient receiving their fitted prosthetic hand. This chapter explores whether improved performance with traditional controllers can be achieved if we improve the environment in which preprosthetic user training takes place.

2.1 Introduction

It is widely acknowledged that fast and effective initial rehabilitation of patients who have acquired an upper limb difference is vital for long-term success and prosthesis use [Roeschlein and Domholdt 1989; Smurr et al. 2008; O’Keeffe 2011; Resnik et al. 2012]. To this end, many training and assessment tools have been developed to assist in training a patient to use their prosthesis after fitting has been completed. However, training during the period of time prior to fitting, known as preprosthetic training, has received far less attention.

Preprosthetic training is vital in both psychologically and physically preparing a patient for life with a prosthetic hand. Physically, the patient must be well practised at performing isolated muscle

contraction needed to operate myoelectric controllers, and their affected arm must be strong enough to support the weight of a prosthetic hand. The psychological needs of such a patient are complex and aspects such as grief are often specific to their circumstance, however managing expectations of future prosthesis use is critical [Smurr et al. 2008; Resnik et al. 2012].

Until recently, in the clinic, prior to receiving their prosthetic hand, patients begin rehabilitation by using simplistic rehabilitation games [Smurr et al. 2008] which may be limited in how well they prepare a user for actually using a prosthetic hand. An emerging idea is to use virtual reality (VR) as a more realistic rehabilitation tool, which has shown benefits in alleviating phantom limb pain [Osumi et al. 2019] and task-specific user training [Dhawan et al. 2019b]. VR prosthetic systems can be used in combination with exercises and even in combination with a physical prosthetic hand to create targeted rehabilitation schedules that are personalised to the patient. Importantly, VR prosthetic systems can potentially enable patients to begin working towards full control of a prosthetic hand at an earlier stage after acquiring their limb difference—before the fitting of a prosthesis even takes place.

Existing VR prosthetic systems typically focus on aesthetic qualities over functionality; the virtual hand is often just a visualisation [Phelan et al. 2021; Resnik et al. 2011], the myoelectric controller driving the virtual hand is not representative of a real prosthetic hand controller [Dhawan et al. 2019b], and object interaction of the virtual hand is generally achieved by ‘attaching’ the hand to the object programmatically [Nissler et al. 2019]. Furthermore, studies identify the need for object weight in virtual reality for more immersive training [Phelan et al. 2021] and have found that force feedback can increase a user’s sense of embodiment of their virtual hand [Snow et al. 2017].

It therefore follows that a VR prosthetic hand system that accurately simulates the functionality and interaction of a real prosthetic hand is needed, and a force feedback system that renders the incidental feedback that would be transmitted through the user’s socket could improve the level of realism achieved by the training environment. Simulation is an important tool in the vast majority of engineered systems, allowing developers to rapidly test and improve designs in a controlled, low-risk setting. A system such as this offers key benefits to both patients and developers; the training environment would offer patients a realistic simulation of their future prosthesis, allowing them to perform rehabilitation tasks usually only possible with a physical prosthesis in the weeks before their fitting, and the simulation would allow developers to rapidly test and evaluate new design and control features for prosthetic hands in an accurate setting with minimal risk. Furthermore, an accurate VR system can be used to create training scenarios specific to user needs, and can be combined with existing rehabilitation methods to provide a higher level of personalisation in rehabilitation.

The work presented in this chapter, summarised in Fig. 2.1, addresses shortfalls in many VR prosthetic hand systems via three main contributions. The first is an accurate VR simulation of the prosthetic device, which in the case of this work is the OLYMPIC hand [Liow et al. 2020]—a modular, tendon-driven prosthetic hand designed at Imperial College London, complete with two

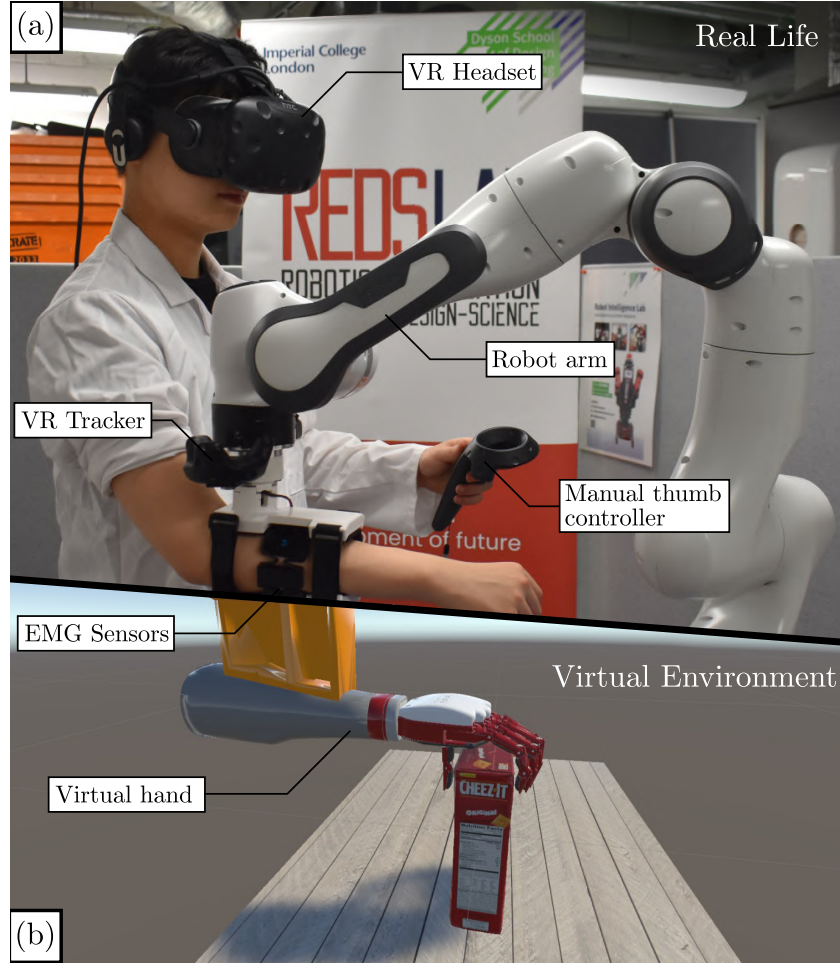


Figure 2.1: The proposed robot-enhanced virtual reality training platform (a) in real life, (b) in virtual reality—the virtual hand is mounted below the forearm of the user. Force feedback that would be felt when wearing a prosthetic hand is rendered from the virtual environment to the user’s forearm using an external robot arm.

degree of freedom (DOF) myoelectric control. Second, an enhanced interaction between the user and the virtual prosthesis provided by an external robot arm rendering realistic forces that the user would feel at the attachment point of their prosthesis. Third, a participant group study targeting the scenario where virtual reality training is used prior to the fitting of the prosthetic hand, comparing the functionality and user perception after training A) using the enhanced system, B) using virtual reality alone, against the real-world OLYMPIC hand when performing the Box and Blocks dexterity assessment [Trombly and Scott 1983] pick-and-place tasks with objects from the YCB object and model set [Calli et al. 2017].

It was found that enhancing virtual reality training with a robot arm improves Box and Block scores and does not significantly reduce pick-and-place performance, compared to training in virtual reality alone. Users perceive that training is closer to using a real prosthesis in terms physical demand and effort. However, limitations in simulation lead to a discrepancy between performance with the virtual hand and the real hand, and an increase in frustration when training with the robot-enhanced (RE) system.

2.2 Related Work

2.2.1 Upper Limb Prosthetic Rehabilitation

Early, specialised rehabilitation as well as managing realistic patient expectations of prosthetic technology are well known to be important factors in avoiding rejection in upper limb prosthesis users [Dakpa and Heger 1997; Watve et al. 2011]. However, rehabilitation after upper-limb amputation is a complex process involving a cross-disciplinary team, and is rarely straight-forward due to the traumatic nature of most injuries that lead to amputation [O’Keeffe 2011; Resnik et al. 2012]. Technology is therefore a critical tool of the prosthetist and occupational therapist in effectively targeting rehabilitation to both provide high quality training and manage expectations of the patient’s future life with a prosthetic hand.

Existing rehabilitation tools used prior to prosthetic fitting are primarily game-based [Smurr et al. 2008; Dawson et al. 2014; Bouwsema et al. 2014; Kristoffersen et al. 2021], and although serious games have found success in other rehabilitation settings, such as for stroke patients [Burke et al. 2009], the games used in clinical prosthetic rehabilitation settings are relatively simplistic and have produced mixed results [Heerschop et al. 2020b; Kristoffersen et al. 2021]. For example, the rehabilitation games presented in [Prahm et al. 2017; Prahm et al. 2019] aim to train patients of recent amputation to activate individual muscles. Although this is useful for very early-stage rehabilitation, it falls far short of preparation for a real prosthesis, and doubts have been raised as to how well myoelectric control skills transfer between tasks [Heerschop et al. 2020b]. Furthermore, any training tool used should be careful not to produce unrealistic expectations of prosthetic control, ability to grasp objects, or other functionality.

2.2.2 Virtual Reality Prosthetic Rehabilitation

In recent years, virtual rehabilitation for prosthetic hand users has become a popular idea [Roche et al. 2014], as a method of training users in an immersive way prior to prosthetic fitting. Virtual reality lends itself well to this style of rehabilitation; the appeal of operating a virtual version of either a human or prosthetic hand is clear, and has been shown to reduce phantom limb pain and other issues surrounding prosthetic hand use [Osumi et al. 2019]. VR also enables the development of immersive rehabilitation scenarios, with some works producing attractive renderings of activities of daily living [Phelan et al. 2021; Nissler et al. 2019; Snow et al. 2017]. Similarly, [Dhawan et al. 2019b] proposes an immersive rehabilitation game setup in which the user must complete three tasks designed to represent activities of daily living. However, in these recent works, although the task and environment may be designed to represent the real-world, the virtual hand is not. A common issue is that the virtual hand is not designed to replicate the function of its real-world counterpart; instead of accurately simulating the motion and interaction of a prosthetic hand, many works predefine a

small number of interactions [Phelan et al. 2021; Nissler et al. 2019; Dhawan et al. 2019b; Hashim et al. 2021] whereby grasped objects ‘attach’ themselves to the prosthetic hand. Naturally, this makes objects easier to grasp than in reality, and leads to prosthesis users performing better in assessment tasks in VR than in the real world [Nissler et al. 2019]. It is clear that in order for VR prosthetic training to be effective the hand should be simulated, rather than animated, and it should interact with its environment with accurate physics. Another major shortcoming in recent work is the level of myoelectric control the user has over the virtual prosthesis. In order to form a realistic training environment, the myoelectric control system used to interpret muscle signals and convert them into desired hand movements should be as close to those used in clinical practice as possible. Yet, multiple works instead use EMG-based gesture recognition systems not designed for prosthetic hand control [Dhawan et al. 2019b; Phelan et al. 2021].

In order to close the gap between virtual reality and the real world, force feedback should be considered. Previous works have highlighted the need for some form of rendering of the weight of the prosthesis in VR prosthetic systems [Phelan et al. 2021]. [Snow et al. 2017] goes some way towards achieving this, using a robot arm to render forces from a simulated prosthetic hand, but its workspace is small, and the work only preliminary. The effect of missing haptic feedback is particularly evident in [Kumar and Todorov 2015], who present a simulated human hand controlled through motion capture of non-disabled users’ real hands. Although accurate hand simulation and high quality control, the functionality of the VR hand is still significantly lower than its real counterpart, with the authors citing feedback as the biggest factor at play.

2.3 Methods

2.3.1 Physical Prosthetic Hand Setup

The OLYMPIC hand [Liow et al. 2020] was used as a test platform for this study. In the hand, five motors control independent flexion/extension of individual fingers, and each motor is equipped with torque and position sensing capabilities (implementation details are given in Chapter 3). The hand was mounted to the forearm of participants without ULD using a 3D printed offset block, shown in Fig. 2.2, which held the hand and accompanying socket below the participants real arm at a distance of ~ 100 mm. The prosthetic hand and participant arm were attached to the mounting block using Velcro straps, where space was left for EMG electrodes.

2.3.2 Virtual Reality Setup

This subsection describes the process of simulating the virtual prosthetic hand and rendering forces at the user’s forearm.

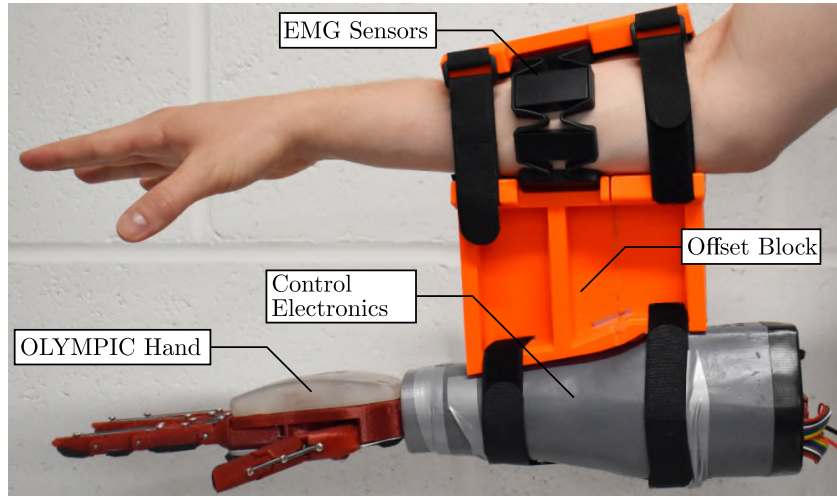


Figure 2.2: The OLYMPIC hand attached to the forearm of a user. Annotated: EMG Sensors, Offset Block, Control Electronics, and the OLYMPIC Hand. To be as close as possible to existing direct control prosthetic control methods, only two of the eight EMG electrodes on the Myo Armband are monitored. No other Myo Armband features were used.

Virtual Prosthetic Hand

To accurately simulate the OLYMPIC hand, a mathematical model of the tendon-driven flexion motion and spring-driven extension motion was developed. As seen in Fig. 2.3, each finger consists of a single tendon actuating three joints, and two springs; one driving the extension of the metacarpophalangeal (MCP) joint, and one driving the extension of the proximal interphalangeal (PIP) and distal interphalangeal (DIP) joints together.

The extension springs of the finger are on the surface of the dorsal side, with the centre-line of the springs at a radial distance of $R + \delta R$ from each joint, so the force in each of these, $F_{i,s1}$ and $F_{i,s2}$ is simply:

$$F_{i,s1} = k_{i,s1}(R + \delta R)(q_{i,1} - \bar{q}_{i,s1}), \quad (2.1)$$

$$F_{i,s2} = k_{i,s2}(R + \delta R)(q_{i,2} + q_{i,3} - \bar{q}_{i,s2}), \quad (2.2)$$

where $\bar{q}_{i,s1}$ and $\bar{q}_{i,s2}$ are the zero-force angles of the first and second extension springs, respectively. Assuming the tendon is light and inextensible, the flexion torque applied to each joint in the finger is equal to $F_i R$. Neglecting dynamics, the torque, $\tau_{i,j}$, on each joint of finger i , taking flexion as the positive direction, is equal to

$$\tau_{i,1} = F_i R - F_{i,s1}(R + \delta R), \quad (2.3)$$

$$\tau_{i,2} = F_i R - F_{i,s2}(R + \delta R), \quad (2.4)$$

$$\tau_{i,3} = F_i R - F_{i,s2}(R + \delta R). \quad (2.5)$$

Note that the torques in the PIP and DIP joints of the finger are identical.

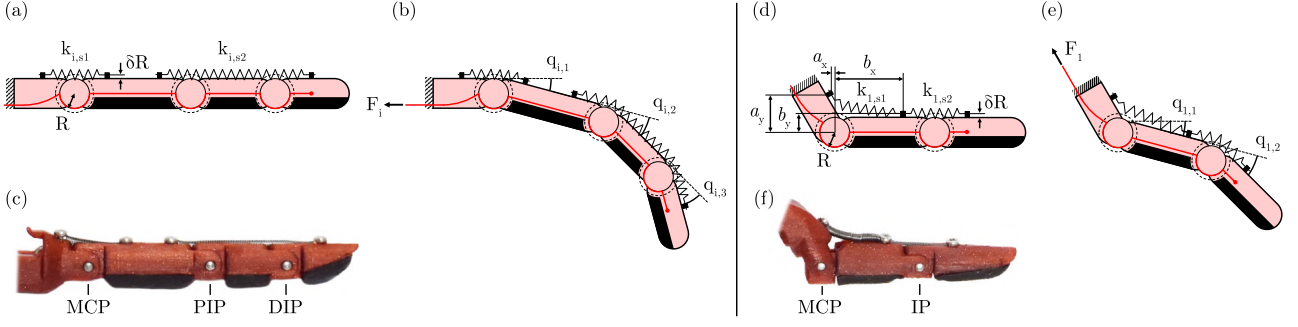


Figure 2.3: Schematic diagram of the fingers and thumb of the OLYMPIC hand, with springs and key dimensions labelled. Left: lateral view of finger i of the OLYMPIC prosthetic hand, (a) relaxed (b) flexed (c) real finger. Right: lateral view of the thumb of the OLYMPIC prosthetic hand, (d) relaxed, (e) flexed, (f) real finger.

The thumb has two joints that move in the flexion/extension direction, the metacarpophalangeal (MCP) joint $q_{1,1}$ and the interphalangeal (IP) joint $q_{1,2}$. The spring force of the thumb is complicated by the offset attachment of the first extension spring, shown in Fig. 2.3. The length, $L_{1,s1}$ of the spring can be calculated as a function of the joint angle $q_{1,1}$:

$$L_{1,s1}(q_{1,1}) = \sqrt{(a_x + b_x \cos \alpha)^2 + (a_y - b_y \sin \alpha)^2}, \quad (2.6)$$

where $\alpha = q_{1,1} - \arctan(b_y, b_x)$. The force in each of the extension springs of the thumb is then equal to

$$F_{1,s1} = k_{1,s1}(L_{1,s1}(q_{1,1}) - L_{1,s1}(\bar{q}_{1,s1})), \quad (2.7)$$

$$F_{1,s2} = k_{1,s2}(R + \delta R)(q_{1,2} - \bar{q}_{1,s2}). \quad (2.8)$$

The perpendicular distance, $d_{1,s1}$, of the first extension spring to the centre of the first joint is:

$$d_{1,s1}(q_{1,1}) = \frac{(a_x + b_x \cos \alpha)a_y + (a_y - b_y \sin \alpha)a_x}{L_{1,s1}(q_{1,1})}. \quad (2.9)$$

The torque on each joint of the thumb is then equal to

$$\tau_{1,1} = F_1 R - F_{1,s1} d_{1,s1}(q_{1,1}), \quad (2.10)$$

$$\tau_{1,2} = F_1 R - F_{1,s2}(R + \delta R). \quad (2.11)$$

As seen in Fig. 2.4, the thumb and index finger of the OLYMPIC hand approximately followed the force-position relationships described in (2.1) - (2.11). As expected, the finger exhibited a linear relationship between motor torque and encoder position, deviating due to periodic gear friction and at points where a new joint overcame its own static friction and began to move. The thumb showed similar characteristics, but due to the offset mounting of the extension spring on the first joint of the

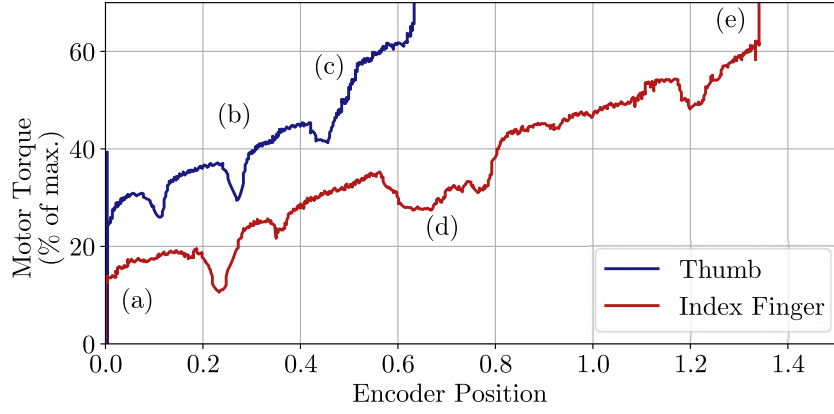


Figure 2.4: The motor torque required to drive to a given encoder position for the thumb and index finger of the OLYMPIC hand. (a) torque required to overcome pre-tensioned springs. (b) friction pattern in the gear driving the thumb. (c) non-linearity caused by the offset spring mounting. (d) static friction overcome as joint begins to move. (e) finger contacts palm.

thumb described in (2.6)-(2.10), the relationship was nonlinear.

The motors that drive the tendon forces have a high gear ratio of 300 : 1, meaning they are not back-driveable. This effect was modelled by adding a barrier term to commanded tendon force $\bar{F}_i$ that was active if the tendon length L_i extended beyond its taut value $\hat{L}_i$ without the motor allowing:

$$F_i = \begin{cases} \bar{F}_i + K_b \max(\hat{L}_i - L_j, 0), & \bar{F}_i \geq 0 \\ 0, & \bar{F}_i < 0 \end{cases}, \quad (2.12)$$

where K_b is a proportional constant set at a suitably high value to prevent backdriving. Position control of each finger was achieved by adding a proportional-integral control loop to the taut tendon length, with desired length $\bar{L}_i$:

$$\bar{F}_i = K_{p,t}(\bar{L}_i - \hat{L}_i) + K_{i,t} \int_0^t (\bar{L}_i - \hat{L}_i) d\tau. \quad (2.13)$$

The OLYMPIC hand was simulated (as shown in Fig. 2.1) in Unity3D (Unity Technologies; USA) as an articulated kinematic tree built on the NVIDIA PhysX engine. At each time step, the torques defined in (2.3)-(2.5) and (2.10)-(2.11) were applied to the joints of the hand. The manually operated thumb abduction and adduction of the simulated hand was controlled via a separate user input from a virtual reality in-hand controller, held in the free hand of the user. Fig. 2.5 shows a visual comparison between the real and virtual OLYMPIC hand while closing the hand. As seen, the hands follow similar trajectories, and reach nearly identical closed positions.

The pose of the base link of the hand was controlled as part of the entire articulation using an extra 6 joints, with the position, $\mathbf{x}$, and orientation of the base of the prosthetic hand driven to a

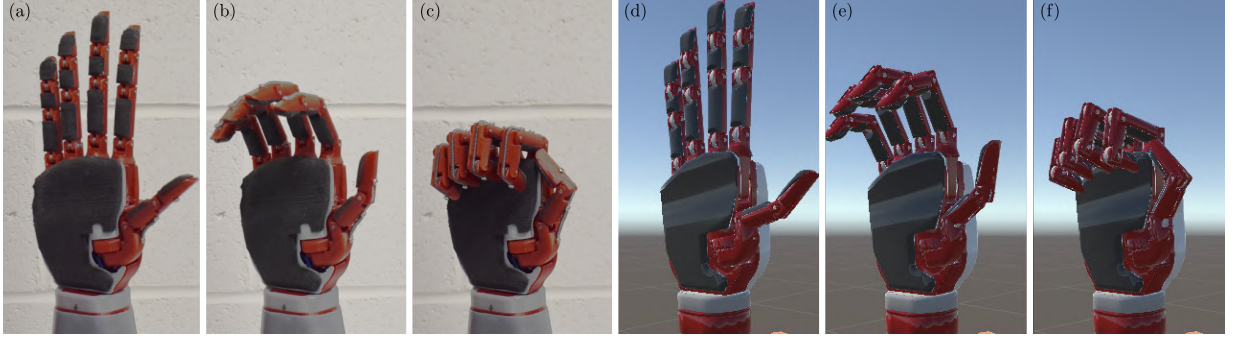


Figure 2.5: A comparison between the real and simulated OLYMPIC hand during a full hand closing action. The real OLYMPIC hand (a) open, (b) partially closed, (c) fully closed. The virtual OLYMPIC hand (d) open, (e) partially closed, (f) closed.

reference tracker pose using a proportional-derivative controller:

$$\mathbf{F} = K_{p,x}(\mathbf{x} - \mathbf{x}_{ref}) - K_{d,x}\dot{\mathbf{x}}, \quad (2.14)$$

$$\mathcal{T} = K_{p,r}\hat{\mathbf{n}}\theta - K_{d,r}\boldsymbol{\omega} \quad (2.15)$$

where $\hat{\mathbf{n}}\theta$ is the relative angle-axis rotation between the reference tracker and the base of the OLYMPIC hand projected into the world frame, and $\boldsymbol{\omega}$ is the angular velocity of the base. This relative rotation represents the rotation from the hand, R_h , to the tracker, R_t :

$${}^hR_t = R_h^T R_t. \quad (2.16)$$

The angle-axis representation of this relative rotation can be extracted by solving:

$$1 + 2\cos\theta = \text{trace}({}^hR_t), \quad (2.17)$$

$$({}^hR_t - I)\mathbf{n} = \mathbf{0}. \quad (2.18)$$

Then, projecting $\mathbf{n}$ to the world reference frame:

$$\hat{\mathbf{n}} = R_t\mathbf{n}. \quad (2.19)$$

Force Feedback Setup

In order to produce the most realistic VR prosthetic hand possible, a robot arm was used to render the forces that the user would experience from a physical prosthesis attached to their forearm. The physics solver governing the motion of the simulated prosthetic hand made use of one of Featherstone's algorithms [Featherstone 2008] to solve forward and inverse dynamics at each time step. The force and torque transmitted to the attachment point of the prosthetic hand to the user was applied by the end effector of a Franka Emika robot arm (Franka Robotics; Germany) attached to the forearm of the

user, as shown in Fig. 2.1.

The robot arm was commanded to apply the wrench defined in (2.14), and (2.15), along with compensation for the robot's own gravity, inertia, joint friction, and a safety term to prevent the robot from reaching its joint limits:

$$\boldsymbol{\tau} = J^T \begin{bmatrix} \mathbf{F} \\ \boldsymbol{\tau} \end{bmatrix} + \boldsymbol{\tau}_g + K_1 H \ddot{\mathbf{q}} + K_2 \Delta \boldsymbol{\tau} + K_3 N(\mathbf{q}_0 - \mathbf{q}), \quad (2.20)$$

where J is the Jacobian of the end-effector of the robot arm, $\boldsymbol{\tau}_g$ is the torque required to compensate for gravity, H is the joint-space inertia matrix of the arm, and $\ddot{\mathbf{q}}$ is its joint accelerations. $\Delta \boldsymbol{\tau}$ is the difference between the compensated joint torques and the measured joint torques at the previous time step, which captures the excess torque that the user must apply to move the robot arm. The null-space projector N was used to apply safety torques in order to keep the robot arm close to a zero configuration $\mathbf{q}_0$ (and therefore away from joint limits) without impacting the wrench applied to the user. K_1 , K_2 , and K_3 are diagonal weighting matrices used to tune the level of compensation at each joint. K_1 and K_2 were tuned to target joints that require a large user force to move, and were carefully set to low values since both apply positive feedback to the user. After tuning K_3 , the robot arm was able to avoid joint limits as the user moved, and maintained this even in the presence of external disturbances. As seen in Fig. 2.6, a user could trace a circle at constant speed by applying a force and torque of their own at the end effector. Without compensation, these forces and torques were slightly increased and the robot arm was unable to avoid joint limits, meaning the user failed to complete the desired trajectory. For safety, the robot arm was limited in maximum force that it could apply, and the robot-user connection was held by an electromagnet that had a holding force of 30 N, which detached the user from the robot when an e-stop was pressed.

2.3.3 Myoelectric Control

A direct control myoelectric control method was used in this study. To simulate existing traditional control prosthetic control methods, only two of the eight EMG electrodes on the Myo Armband (Thalmic Labs; USA) were utilised. The first electrode was positioned in the inner forearm to detect muscle activity during wrist flexion while the second electrode was positioned on the antagonistic muscle group on the outer forearm to detect wrist extension. A binary control system similar to the traditional binary controller in (1.3) was implemented — if the signal on the wrist flexion electrode passed a threshold then the motor on each finger was driven to fully close the hand, if the signal on the wrist extension electrode passed a separate threshold then the hand opened:

$$\bar{L}_i = \begin{cases} L_{min}, & i_1(k) \geq I_1 \\ L_{max}, & i_2(k) \geq I_2 \end{cases}, \quad (2.21)$$

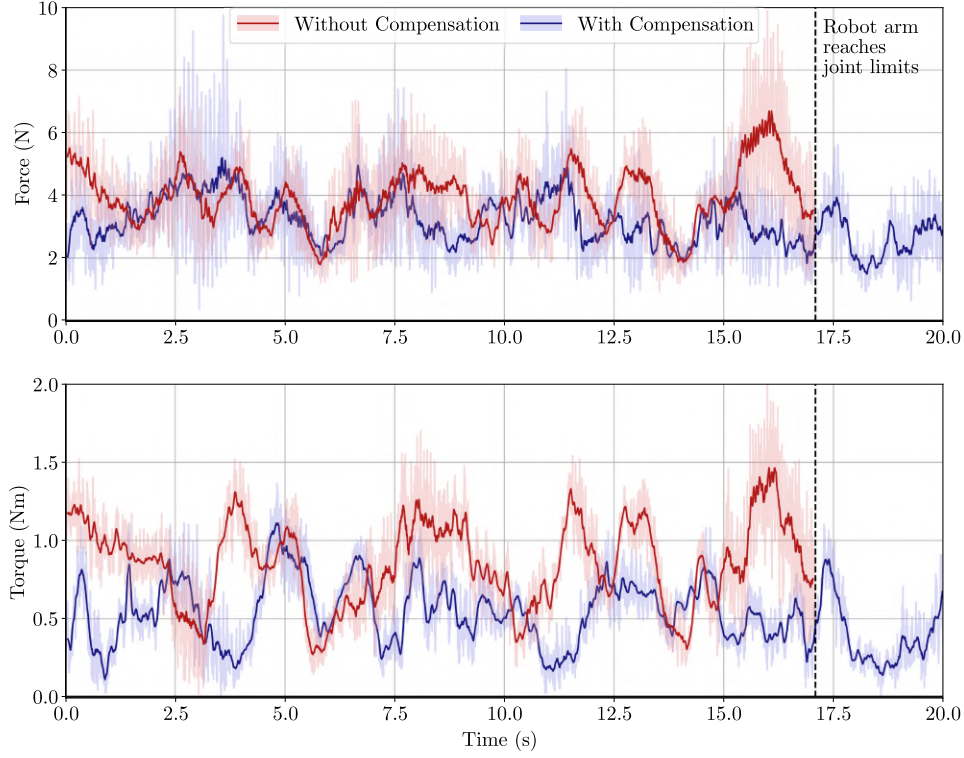


Figure 2.6: The magnitude of the force (top) and torque (bottom) applied by the user to trace a circle at constant speed while attached to the robot arm. Blue - with compensation, red - without compensation. Without compensation the robot arm reaches joint limits and the user is unable to complete the trajectory.

where $i_1(k)$ and $i_2(k)$ are the post-processed values read from the two electrodes at sample k , and I_1 and I_2 are tuned thresholds that are personal to each user. This method of control was chosen because traditional control methods are common in prosthetic hands available to patients, and offered a robust baseline with which to test the virtual reality platform.

2.3.4 Assessing Task Performance

To assess how well users could be trained for physical prosthesis use with the VR prosthetic system, two control group experiments were performed. In each experiment, participants completed a number of sets of timed pick-and-place exercises (each set is henceforth referred to as a trial) in training before transitioning to use the physical prosthetic hand for a number of test trials. Participants were placed into three groups: a VR group, who performed training trials in virtual reality, a RE group, who performed training trials in virtual reality with the robot arm providing force feedback, and a Control group, who performed no training trials. Participants without upper limb difference were recruited for each group, and are particularly useful for this work because they had no prior experience controlling prosthetic hands, and could therefore be considered naive users. The use of human participants in the experiments in this chapter was granted ethical approval by the Imperial College London Research Governance and Integrity Team (RGIT), Science Engineering and Technology Research

Ethics Committee (SETREC) number 21IC6716. Written consent was obtained from participants prior to taking part in the study.

The Box and Blocks dexterity assessment [Trombly and Scott 1983] (shown in Fig. 2.7 left) was used for the first experiment, in which 10 training trials were performed, then 5 test trials with the physical prosthetic hand. In each trial, participants were given 60 seconds to transfer as many individual blocks from one box to another, with a higher number of blocks representing a higher level of dexterity. 5 participants were recruited to each group, giving a total of 15 participants. To test for statistical significance between Box and Blocks results, Wald Chi-Squared tests were used with generalised estimating equations models fit to results using SPSS (IBM; UK), with a Poisson loglinear model type to account for Box and Blocks scores being counts of transported blocks, rather than continuous variables.

For the second experiment, ten objects from the YCB object and model set [Calli et al. 2017] (shown in Fig. 2.7 right) were used to explore user dexterity across a wider range of objects that are representative of objects used in activities of daily living. Five training trials were performed, followed by five test trials in order to provide a direct comparison between the virtual and physical setups. In each trial, each of the ten objects were grasped, lifted, then transferred 500 mm, before being placed, as in [Liow et al. 2020]. In this work, the pick and place action was timed to offer a more detailed measure of functionality, similar to other dexterity assessments such as the Southampton Hand Assessment Procedure [Light et al. 2002] or the Box and Block Test [Trombly and Scott 1983]; a quicker time to complete a pick and place task is thought to correspond to better hand functionality. Average pick and place time over a trial was recorded. Three participants were recruited to each group, giving a total of nine participants in this experiment. To test for statistical significance between YCB pick and place timed results, Wald Chi-Squared tests were used with generalised estimating equations models fit to results using SPSS (IBM; UK), with a linear model type suitable for the continuous time result.

2.3.5 Assessing User Perception

User perception is an important aspect of prosthesis use that is often neglected. To assess user perception of the system, each participant completed a supplementary questionnaire and a copy of the NASA Task Load Index, also known as the NASA-TLX [Hart and Staveland 1988], first after completing the training trials, then after the test trials of the YCB pick-and-place experiment (it should be noted that the Box and Blocks experiment contains more training trials than testing trials, so cannot be compared). The NASA-TLX contains questions assessing mental and physical demand, temporal demand, task performance, effort, and frustration. The questionnaire was completed by each participant after training and again after testing. In this study, ‘raw’ TLX scores were recorded, scaled between 0 and 100, as they allow for direct comparison between each aspect of task load [Hart

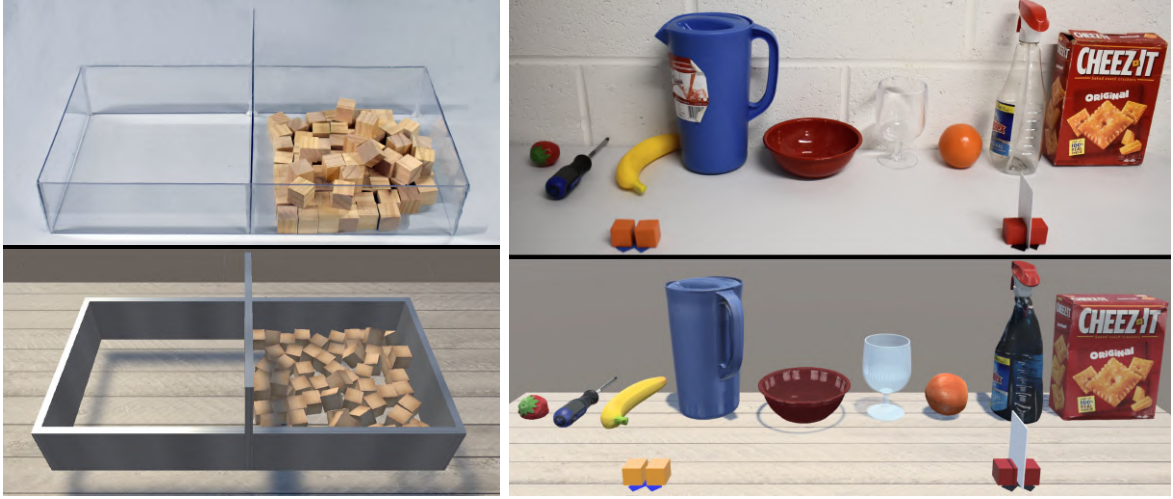


Figure 2.7: The real (top) and simulated (bottom) experimental setups used in this work to train and evaluate user ability to perform pick and place actions with the prosthetic hand.

2006].

2.4 Results & Discussion

Average Box and Block scores of each group for the ten training trials and five test trials are shown in Fig. 2.8. As seen, neither group performed as well in training as with the physical prosthetic hand. Both groups performed significantly differently during the ten training trials to the control group during the five testing trials (both $p < 0.001$). However, the RE group performed consistently better in training than the VR group ($p < 0.05$). After transitioning onto using the physical prosthetic hand, the RE group significantly outperformed both the VR group and the Control group across the five test trials ($p < 0.1$ and $p < 0.05$, respectively). No significant differences in Box and Block scores were observed between the VR and Control group in testing.

Average YCB pick-and-place times of each group for the five training trials and five test trials are shown in Fig. 2.8. Again, both the VR and RE group performed significantly worse in training than the control group (both $p < 0.001$), however in this experiment the RE group performed comparably to the VR group in training. When transitioning to the physical prosthesis, the VR group were unable to adapt within the five test trials, and performed significantly worse than the Control group ($p < 0.05$). No significant differences between the RE group and the Control group during testing were observed.

It is clear that there is a gap between the virtual and physical prostheses that prevented users from attaining real-world performance on the chosen pick-and-place tasks. One major source of this that is common to both the VR and RE groups is that the simulation relied on rigid-body collisions; the real-world prosthesis was equipped with soft silicone pads that deform on contact to provide a better grip. Features such as these are particularly important when grasping small objects such as the blocks present in the Box and Blocks test, or objects of irregular shape such as the screwdriver in

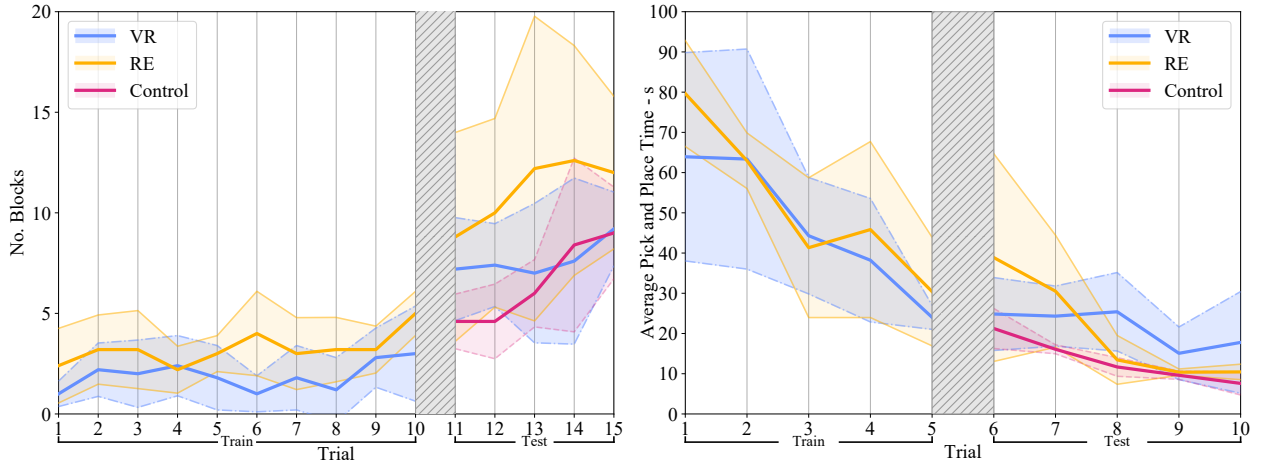


Figure 2.8: Participant results using the virtual reality prosthetic hand in training trials, then the real prosthetic hand in testing trials. Left: Average Box and Block scores of user groups across 10 training trials and 5 test trials. Right: Average pick-and-place times of YCB objects of user groups across 5 training trials and 5 test trials. Shaded regions represent ± 1 standard deviation. VR - virtual reality group, RE - robot-enhanced group, C - control group.

the YCB object set, and it was not possible to simulate accurately with existing physics simulators. Furthermore, the collision geometry used in the simulation was an approximation of the collision geometry of the physical hand. Small features and irregularities on the surfaces of the physical hand can also improve grasping ability, but were not present in the virtual prosthesis. Despite this gap, RE training resulted in improved physical prosthetic hand performance compared to VR training alone. Furthermore, results with the YCB objects indicate that VR training alone could even be detrimental to performance when going on to use a real prosthesis, although a larger participant group would be required to validate this fully. A result that is perhaps surprising is that RE training had a significant impact on Box and Block performance, whereas VR training did not. The force feedback from the robot arm may have allowed users to identify with greater certainty whether the virtual hand was in contact with its surroundings when attempting to grasp a block, which, during use, can prevent the hand from closing successfully.

Group NASA-TLX responses for the VR, RE, and control groups are shown in Fig. 2.9. In the majority of cases, responses of participants during training with the RE platform were much closer to responses of the control group. In both the Box and Blocks Test and the YCB pick and place task, physical demand during training of the virtual reality group was lower than the RE group. However, the lack of force feedback in the VR group lead to a higher perceived physical demand when using the real world prosthesis during testing, something that was particularly pronounced for the YCB pick and place task. The RE group experienced a higher physical demand during training than the control group, especially during the Box and Blocks Test — this may have been due to the inertia of the robot arm. Even after inertia compensation, it was impossible to completely reduce this effect, and performing repetitive oscillatory movements (i.e. performing the Box and Blocks Test) may have exacerbated this. In both task sets, the RE group exhibited a higher perceived effort and frustration,

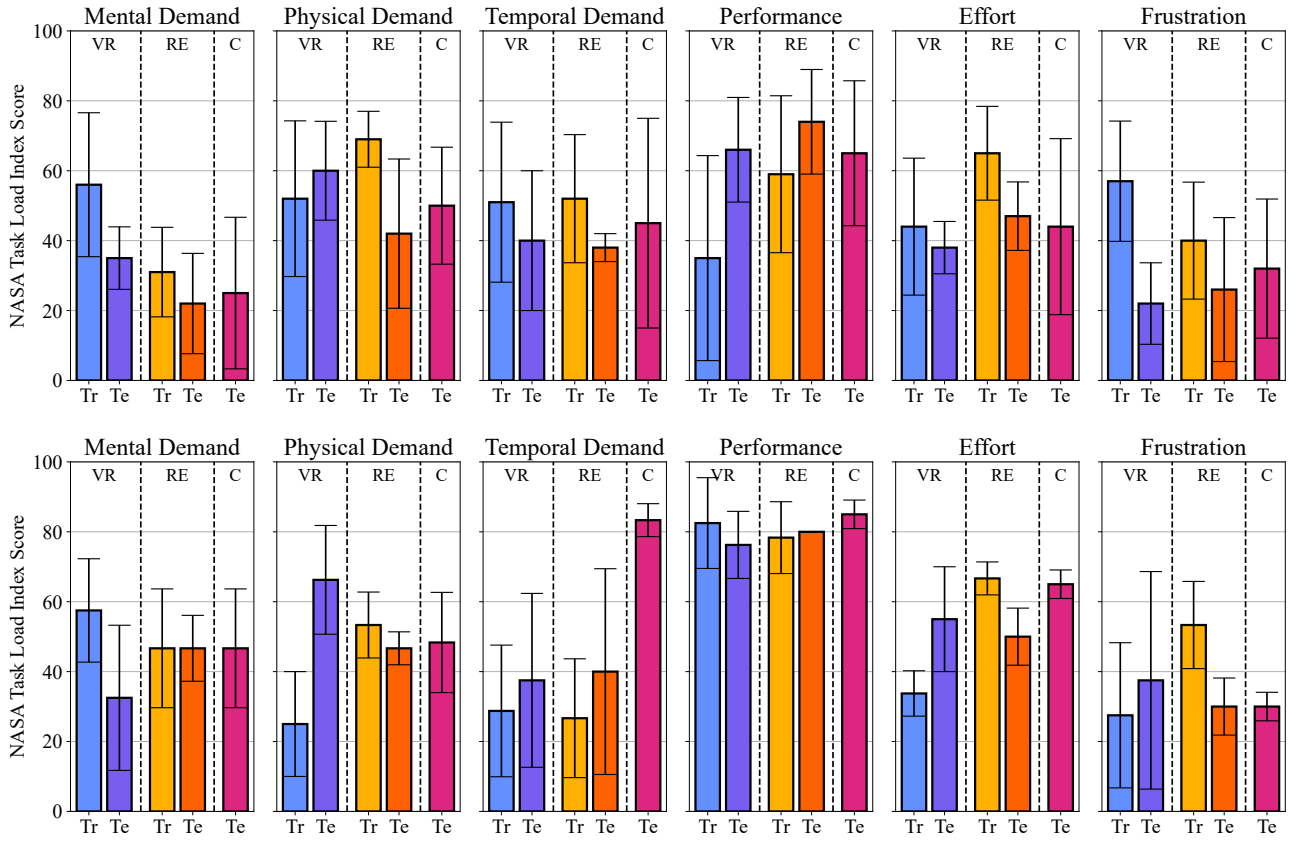


Figure 2.9: Mean (standard deviation shown) NASA Task Load Index responses for each participant group after training (Tr) and testing (Te). VR - virtual reality group, RE - robot-enhanced group, C - control group. Top: participant responses for the Box and Blocks Test. Bottom: participant responses for the YCB pick and place task.

which then reduced to be either equal or lower than the control group during testing. The VR group were much more inconsistent, with effort and frustration increasing from training to testing on the YCB pick and place task, and decreasing for the Box and Blocks Test.

TLX results highlight an important shortcoming in VR training alone; training without realistic force feedback may lead to an unrealistic expectation of the physical demand and effort required by the user. Further to this, greater variance in VR group responses could be detrimental to rehabilitation, as it indicates that it may be difficult to predict how someone will respond to VR training. This issue was not present in the RE group, however the RE group found training more frustrating than the control group found using the real prosthetic hand. This could have been caused by the aforementioned discrepancies between simulation and reality, making grasping objects more difficult than expected, coupled with the weight of the prosthetic hand amplifying user frustration. After the RE group transitioned to using the physical prosthesis this frustration was alleviated, returning to control levels, indicating that training with the RE system was not detrimental to user frustration in the long term. In fact, in the YCB pick and place task, the RE group results for effort were lower than control results after testing trials, giving hope that RE training may be beneficial for user perception when transitioning to using a real prosthesis.

2.5 Conclusions

In this chapter, a virtual reality platform for preprosthetic hand training was presented, which was enhanced by utilising a robot arm to render force feedback to the user. Significant shortcomings in existing virtual and augmented reality prosthetic training systems were addressed by developing an accurately simulated prosthesis, using clinically relevant traditional myoelectric control technology, and force feedback.

Experimental results with participants without upper limb difference show that training with the RE platform improved user performance on the Box and Blocks dexterity assessment significantly compared to both the group of participants who had trained in virtual reality alone, and the control group who had received no prior training. On more complex pick-and-place tasks with YCB objects, the final performance of the RE training group were comparable to the control group, whereas training in purely virtual reality resulted in a significant reduction in performance. Results of the NASA-TLX questionnaire show that training with the RE system was comparable in terms of physical demand and effort to directly using the real prosthesis — a considerable improvement over training in VR alone. However, limitations of rigid-body simulation create discrepancies between the simulated and real hand that lead to an increase in frustration during RE training, which was exacerbated by force feedback applied to the user. This was alleviated when transitioning to the real prosthesis. This work has shown that this platform can be an effective tool to prepare users for prosthetic hand use, without producing negative side-effects such as non-representative control and interaction, and unrealistic user expectations. Although the focus of this chapter has been on the post-amputation to pre-fitting period for adults who acquire their upper limb difference later in life, a related application of the technology is to allow potential prosthetic hand users to try a range of possible myoelectric hands before committing to purchasing one — given the high cost of clinically available myoelectric prostheses, this is an appealing prospect.

It is clear that more effective training environments are possible for potential prosthetic hand users when technology—in this case virtual reality and force feedback—is utilised. Perhaps the most important finding is that users actively performed worse when faced with training that was not representative of real use. In order for traditional myoelectric controllers to be used to their full potential, training must be representative of daily use.

Chapter 3

Advancing Discrete Control

This chapter is based on the work presented in:

Digby Chappell, Zeyu Yang, Honn Wee Son, Fernando Bello, Petar Kormushev, and Nicolas Rojas (July 2022b). “Towards Instant Calibration in Myoelectric Prosthetic Hands: A Highly Data-Efficient Controller Based on the Wasserstein Distance”. In: *IEEE International Conference on Rehabilitation Robotics (ICORR)*. Rotterdam: IEEE, pp. 1–6

Zeyu Yang, Angus B. Clark, **Digby Chappell**, and Nicolas Rojas (May 2022). “Instinctive Real-time sEMG-based Control of Prosthetic Hand with Reduced Data Acquisition and Embedded Deep Learning Training”. In: *2022 International Conference on Robotics and Automation (ICRA)*. IEEE, pp. 5666–5672

Pattern recognition control, a subset of discrete control and a popular direction for prosthetic hand control research, involves classifying user muscle activity as a desired gesture or grasp. Many modern works approach this with computationally heavy machine learning approaches and with expensive sensors that are not available to real prosthetic hand users. This chapter investigates methods of achieving high performance with pattern recognition control without increasing setup complexity, cost, or usability.

3.1 Introduction

The most popular method of controlling prosthetic hands is via some form of discrete control; moving the prosthesis between fixed (discrete) positions or gestures. As introduced in 1.2.2, discrete control takes many forms—simple thresholding and other traditional control methods are indeed discrete—but the focus of this chapter is on methods that seek to classify patterns of muscle activity as pre-recorded references, also known as pattern recognition control. Improving classification accuracy and increasing the number of references available to the user have been the focus of research dating back to the 1960s [Finley and Wirta 1967], and a large number of modern works have used machine learning

techniques to attain these goals [Tsinganos et al. 2018; Jafarzadeh et al. 2019].

From a user perspective, there is often an undesirable trade-off between ease of use and controller performance. Machine learning-based controllers often rely on a large amount of training data specific to each user, and utilise a large number of trainable parameters, both of which are unsuitable for the embedded controllers used in prosthetic hands [Farina et al. 2014], and calibration can be a difficult process in which a large amount of new training data must be collected to update many model parameters. A similar trend is to use a greater amount of electrodes to obtain more detailed EMG data for classification [Tam et al. 2019; Zanghieri et al. 2019], however this also adds signal processing complexity and adds cost to the device. In order to be adopted for widespread use, controller performance, simple calibration, ease of use, and robustness are all important for next-generation myoelectric controllers [Smail et al. 2020; Farina et al. 2014]. The vast majority of recent research has focused on the former; developing more and more complex models to attain diminishing returns in pattern recognition tasks [Tsinganos et al. 2018; Jafarzadeh et al. 2019], and while improved performance is necessary to minimise the risk of prosthesis abandonment [Kumar et al. 2019], it is clear that it must not come at the cost of how suitable these controllers are for daily use by prosthetic hand users.

It follows that there is a need for prosthetic hand control algorithms that are able to classify multiple patterns of muscle activity at a similar level to modern controllers, but do not sacrifice other important factors such as robustness, cost, and ease of calibration.

In this chapter, two methods of advancing discrete control are introduced. The first method is to expand the control and computational capabilities of a prosthetic hand, allowing advanced pattern recognition controllers to be trained and rolled out entirely on the prosthesis itself. As a demonstration of this capability, an embedded controller is presented that utilises minimal EMG electrodes to classify eight patterns of muscle activity. The second method is a distance-based classifier that uses a single snapshot of user data for each class, and provides interpretable classification results. The embedded controller is tested with participants without ULD, while the distance-based classifier is tested with participants both with and without ULD. Both controllers are shown to perform comparably to more complex controllers with greater numbers of electrodes and controllers which are more computationally intense.

3.2 Related Work

The topic of EMG signal classification has been the focus of research dating back over six decades [Finley and Wirta 1967; Almström et al. 1981; Hudgins et al. 1993]. Historically, traditional signal processing and statistical methods have been limited in performance, either having a low accuracy, or only classifying one or two grasps [Englehart and Hudgins 2003]. Classical machine learning methods such as Support Vector Machines (SVMs) [Alkan and Günay 2012; Rossi et al. 2015; Tavakoli

et al. 2018], Hidden Markov Models [Rossi et al. 2015], and K-Nearest-Neighbours [Haris et al. 2015] achieved more satisfactory, but still limited, results. More recently, thanks to developments in deep learning, research progress has been made in the area utilising models such as convolutional neural networks (CNNs) [Atzori et al. 2016; George et al. 2018], long-short term memory (LSTM) networks [Xia et al. 2018; Jabbari et al. 2020; Simão et al. 2019; Samadani 2018], gated recurrent unit (GRU) networks [Simão et al. 2019; Samadani 2018], and attention-based mechanisms [Samadani 2018; Hu et al. 2018]. However, most of these approaches are still far from commercial viability due to a lack of individualised user training data, poor real-time performance [Parajuli et al. 2019], computational limitations in embedded systems, and high cost. In particular, a lack of training data from individual users makes calibrating deep learning-based controllers a difficult, time-consuming process of collecting a large amount of reference EMG data from users.

In order to address the issue of calibration, some works have investigated transfer learning in order to transfer a complex controller, trained on a large dataset, to individual users [Demir et al. 2019; Côté-Allard et al. 2019; Rahimian et al. 2021]. However, the models used in these works are an order of magnitude larger than controllers trained specifically to single users, as they must also capture subtle differences between users, and must therefore be trained on an external computer before being implemented on the target prosthesis. Further to this, presented controllers are rarely tested on actual prosthetic hand users, who exhibit a high degree of heterogeneity in muscle activity post-amputation [Waris et al. 2018], and moreover are often not validated on physical tasks, instead opting to test classification accuracy with participants without ULD [Rahimian et al. 2021; Côté-Allard et al. 2019]. Naturally, transferring controllers to new participants without ULD will be more successful than transferring controllers to participants with ULD — both congenital and traumatic limb differences result in extreme heterogeneity to the residual muscles in the upper limb.

Another approach is to train the classifier from data collected directly from the user on the prosthetic hand itself using an embedded microcontroller (MCU). Historically, microcontrollers have not been powerful enough to satisfy the high computational demands of various deep learning techniques, however, thanks to the improvements in computing power of microcontrollers, researchers have recently been able to implement and analyse the performance of embedded deep learning-based EMG classifiers. For example, [Tam et al. 2019] implemented a CNN based classifier on a Jetson Nano MCU, and [Zanghieri et al. 2019] implemented a temporal convolutional network based on a GAP8 MCU. [Nguyen et al. 2021] implemented a GRU based classifier on a consumer-level Nvidia Jetson Nano MCU, and additionally tested the classifier on a prosthetic hand to verify its practicability in a clinical/real-world scenario. Despite this progress, among each of the aforementioned embedded solutions, none of them trained their controller on the embedded processor itself. The need for a powerful computer for the setup and calibration of the prosthetic hand adds to the cost and complexity of the system, and jeopardises usability by users of different backgrounds and accessibility to technology.

An increased level of hardware sophistication, such as a larger number of electrodes or the addition of computationally capable microcontrollers needed to run deep learning-based controllers, incurs a cost that is inevitably passed downstream to the user. Given that adults with ULD have historically been found to be from lower income groups [Kejlaa 1992; Østlie et al. 2011c], and some face challenges returning to work [Sluis et al. 2009], reducing the cost of next-generation prosthetic hand controllers is an important challenge.

3.3 Embedded Discrete Control

This section presents a method of achieving entirely embedded advanced pattern recognition control of the OLYMPIC hand, focusing on signal processing steps and a demonstration of a machine learning-based controller trained on data individual to each user.

3.3.1 Hardware Modifications

In order to remove the need for an external computer when calibrating a myoelectric controller on the OLYMPIC hand, a series of hardware modifications were made. These include position and torque sensing on each motor, a NVIDIA Jetson Nano microcontroller housed in the forearm, a fibreglass composite forearm, and a modular wrist connection [Yang et al. 2022]. Following these modifications, the mass of the hand and forearm combined was 1.426 kg.

Control

With electrical current and position sensing capabilities, the torque and position of each motor could be controlled. Two proportional-integral (PI) control loops were used. The inner loop controlled the current draw (torque) by sending a command torque τ_{cmd} according to the desired torque τ_{des} and actual torque of the motor τ_{act} :

$$\tau_{cmd} = K_{\tau,p}(\tau_{des} - \tau_{act}) + K_{\tau,i} \int (\tau_{des} - \tau_{act}) dt. \quad (3.1)$$

The position of the motor was controlled with an outer loop acting on the error between the desired motor position p_{des} and actual position measured with the encoder p_{act} , generating a desired torque for the inner loop:

$$\tau_{des} = K_{p,p}(p_{des} - p_{act}) + K_{p,i} \int (p_{des} - p_{act}) dt. \quad (3.2)$$

Monitoring the current and position of each motor also meant that finger contact could be detected. The torque of each finger of the motor sharply increased when contact was made, and the motor was unable to rotate, so encoder position halts. This enabled contact detection and therefore grasping of more delicate objects to be achieved.

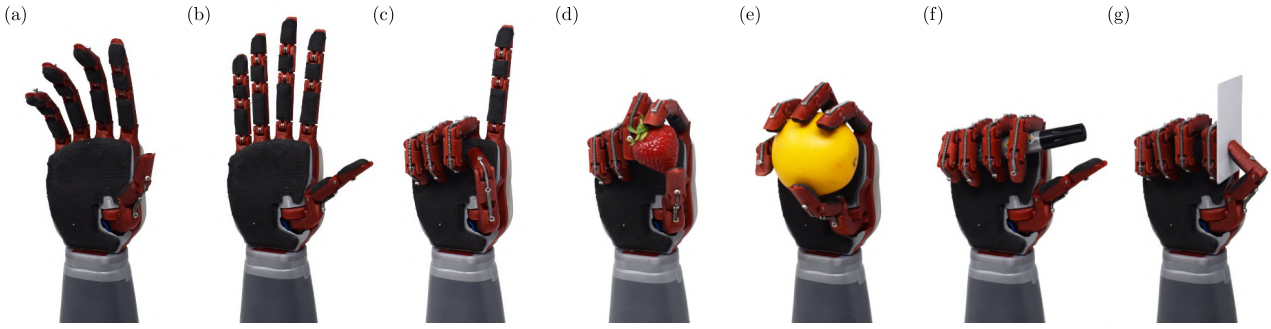


Figure 3.1: The default, grasping, and gesture configurations implemented on the OLYMPIC hand. (a) Relax (default position), (b) Open Palm and (c) Index Finger Point (gestures), (d) Tripod Grasp, (e) Power Grasp, (f) Tool Grasp, and (g) Lateral Pinch (grasps).

3.3.2 Demonstration of Embedded Discrete Control

To demonstrate the ability of the modified hand to perform advanced myoelectric control, a machine learning-based pattern recognition controller was trained directly on the embedded microcontroller, on data individual to each user.

Classifier Implementation Details

Eight (seven plus idle) grasps and gestures were targeted for classification: power grip, tool grip, tripod pinch, lateral pinch, index finger point, open palm, and relaxed pose, selected based on the GRASP taxonomy [Feix et al. 2016] to cover a range of power and precision grasps. As shown in Fig. 3.1, the set consisted of a balanced mixture of precision grasps, power grasps, and gestures, thus providing a foundation to perform a variety of day to day tasks. In addition, an idle state was also needed for the system to recognise when there was no grasping action at all.

Instead of trying to recognise the EMG signal when a grasp is active (steady state), a change of state from idle to a class was targeted, and a common action was used to return the prosthesis to resting pose. This was motivated by two factors. The first is that gestures apply no static force and therefore generate a comparatively small EMG signal when reached, so classifying steady state gestures is inherently difficult. Second, having users maintain a steady state pattern of muscle activity can become tiring.

Only two electrodes were utilised for this controller, so a relatively large window of 1.5 seconds was used as the input to the classifier. The electrodes used were the hobbyist-level MyoWare Muscle Sensors, which use wet adhesive contact pads. The raw EMG signal from the two electrodes fed into a precision differential amplifier, followed by two amplifiers, a rectifier, and an integrator. The output of these analog preprocessing steps was the envelope of the raw EMG signal, which was directly input to the Jetson Nano MCU. The targeted areas of the forearm were anterior and posterior regions, corresponding to the bulk muscle responsible for flexion and extension of the fingers of the hand, respectively.

Crossing the analogue and digital domains, the Jetson Nano sampled the incoming EMG envelope

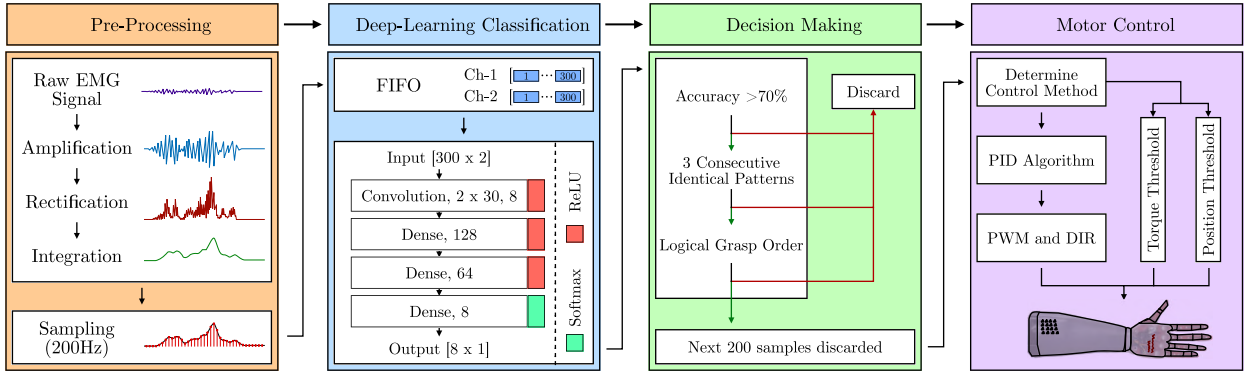


Figure 3.2: Signal processing steps showing key stages of pre-processing, deep learning classification, decision making, and motor control.

at 200 Hz. Raw EMG signals have a bandwidth of 500 Hz [Shaw and Bagha 2012], however the integrator step in filtering discards many high frequency components, so a lower sampling rate was acceptable given that fast temporal features were not utilised in classification. The sampled EMG data input to a 300 sample FIFO, corresponding to the 1.5 second window. The trained neural network was inferred every 20 new samples of the EMG signal, i.e. a new prediction was generated every 0.1 seconds. The predictions fed into a decision making chain: first, the inference must have a confidence greater than 70%. Second, three consecutive identical predictions were required. Third, the prediction was required to be feasible (a grasp needed to be unlocked by entering the relaxed state before another grasp could be attempted). If the three criteria were all satisfied, the result would be sent to the motor controller to actuate the prosthesis. Finally, predicted actions of the following second were blocked to avoid any post-grasping-action signal from leading to incorrect results. The overall signal processing flow can be seen in Fig. 3.2.

30 repetitions for each of the eight classes (seven grasps + idle state) were collected to train the classifier. Each user was asked to perform the reference action within the 1.5 second time window. Data augmentation was used to generate more training data in order to improve the generalisation ability of the model. Three data augmentation strategies, inspired by computer vision/image recognition, were used: random shift, random zoom, and random contrast, corresponding to the start time, speed, and amplitude variations of the grasping action of the user during the data collections.

Controller Evaluation

The time requirement for calibration was evaluated. Five users without upper limb difference were asked to perform 30 repetitions of each grasp in turn. A four-second interval before and between the 30 repetitions was used to allow the user to rest and prepare for the next repetition. The users were asked to perform the grasp or gesture action approximately 0.5 seconds into the recording period, which ensured that the entire action was recorded. Users were asked to perform the grasp and gestures exactly as they normally do in real life. To try to encourage consistency, the real-time EMG signal was shown on a display in front of the users. For the relaxed state, users were asked to shake their

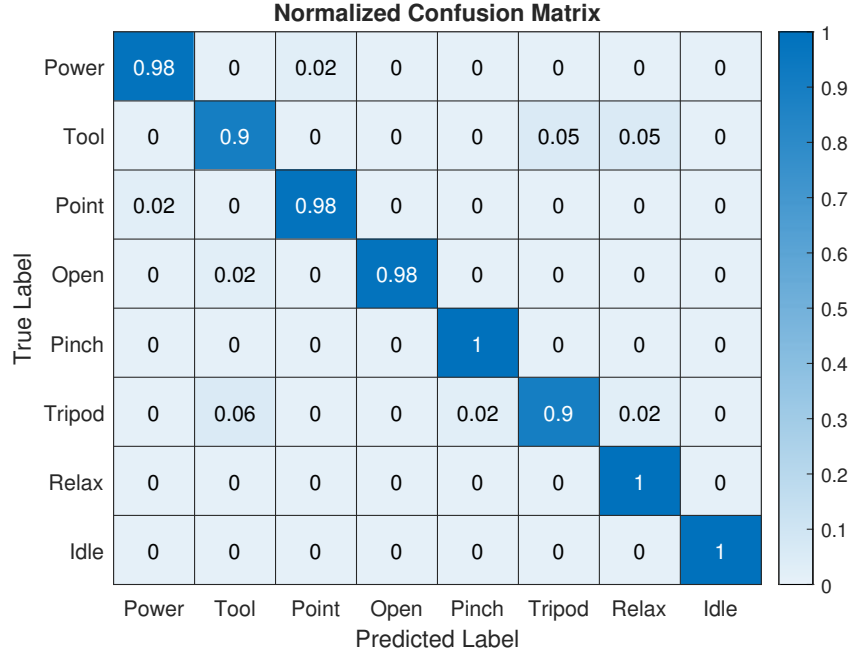


Figure 3.3: Average confusion matrix of the five trained user classifiers making predictions on their respective validation datasets.

hand, as they would to relax a stiff tired muscle. The entire data collection process took less than 30 minutes to complete for each user. The collected data were randomly split into training and validation sets at a ratio of 7 : 3. The model trained with a categorical cross-entropy loss function, and Adam optimiser with learning rate of $1e - 4$. The model trained for 30 epochs with a batch size of 8, taking approximately 55 seconds.

On average of the five users, the validation accuracy of the classifier converged at around 20 epochs, at a value of 96.68%. Fig. 3.3 shows the average confusion matrix of the classifiers trained on each user, making predictions on their respective validation datasets. As seen, all of the grasps had a sensitivity greater than 90%, with lateral pinch and idle showing greatest sensitivity and specificity. Tripod and tool grips showed the worst performance, although sensitivity was still above 90%.

The performance of the classifier in terms of both accuracy and latency was tested on a real-time continuous EMG signal. Users performed 90 grasps in total each in a random pre-determined order, with 15 repetitions for the six targeted grasps and gestures. Participants were asked to perform the grasps in the order, and then release the grasp to the relax state, at a pace they felt comfortable. Upon a wrong prediction, the participants needed to re-attempt the action until a correct prediction was made. The Jetson Nano performed the real-time classification, continuously outputting the most up-to-date prediction at the 10 Hz inference frequency. The number of tries it took to get a correct prediction, and the time delay between the end of hand movement to the correct prediction were recorded.

During roll out, participants achieved 79.11% accuracy on first attempt at performing each action, and 96.22% accuracy within two attempts. Interestingly, an increase in accuracy throughout the 90 repetitions was observed. Shown in Fig. 3.4 is classification accuracy over a 30-repetition window

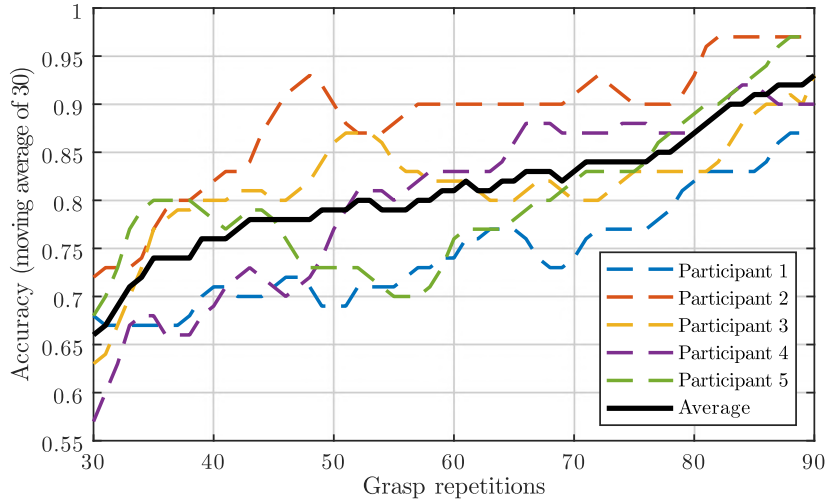


Figure 3.4: Average first attempt control accuracy of users performing target actions with real action feedback over 90 test repetitions, smoothed with a 30 sample moving average.

through the 90 repetitions; the first attempt average accuracy started at 66%, and gradually increased to 93% by the end. As found in literature, the feedback given to users as they tested the controller was important in this increase in performance [Bouwsema et al. 2014].

The average latency of a correct grasp was at 1.097 seconds, with a standard deviation of 0.307 seconds. The value was expected due to the setup protocol, as the participants were asked to perform the grasping action 0.5 seconds into the 1.5 second window. The total time for the participants to finish the 90 repetitions was no longer than 20 minutes.

For data collection, and therefore for calibration, the amount of training data needed was minimal. The size of all the training data were less than 2 MB, which is suitable for an embedded micro-controller. More importantly, the time needed to collect all the training data was only 30 minutes; together with automated guidance, the data collection procedure was relatively quick and user friendly. This, together with a fast neural network training time, makes the controller suitable for use by real prosthetic hand users. This discrete control demonstration highlights how personal myoelectric controllers can be trained directly on a prosthetic hand with a small amount of user data, given that the prosthesis is equipped with reasonable control and computational capabilities.

3.4 Advanced Discrete Control with Minimal User Data

This section presents a method of achieving advanced pattern recognition control using the bare minimum amount of user data. This was achieved by using a distance-based classifier that provides interpretable discrete control of multiple gestures and grasps.

3.4.1 Muscle Activity Space

At the core of the distance-based controller is the idea that muscle activity can be thought of as occupying a space according to the spatial setup of the electrodes recording EMG. The statistical

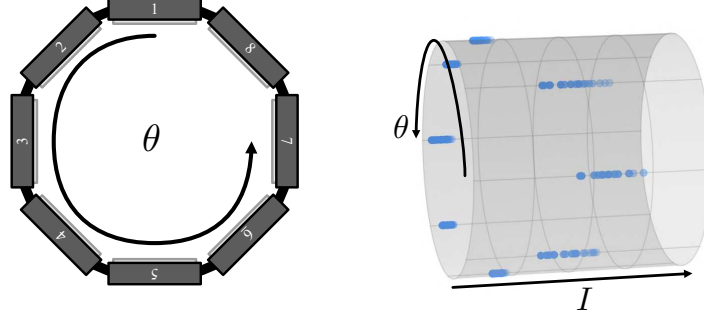


Figure 3.5: The cylindrical space of electromyography (EMG) data sampled at eight locations around the forearm. Left: The circumferential position θ of each of the eight electrodes in the Myo armband. Right: Illustrative cylindrical space that EMG samples lie on, with the I axis corresponding to the intensity of mean absolute value samples, and θ axis corresponding to the circumferential position of the sample around the forearm.

properties of observed signals on this space can be used to obtain information such as how ‘far apart’ two sets of samples of muscle activity are, which can in turn be used for control purposes.

EMG Data Acquisition

In this controller, to record EMG signals from the forearm of the user, a Thalmic Labs Myo armband was used. The armband sampled surface EMG at a rate of 200 Hz at eight equally spaced points around the forearm (see Fig. 3.5). Pre-processing was performed to rectify and generate the envelope of the incoming samples. For recorded signal $s(k)$ at sample k , the mean absolute value (MAV) $I(k)$ over $W = 10$ samples is equal to

$$I(k) = \frac{1}{W} \sum_{w=1}^W |s(k + w - W)|. \quad (3.3)$$

This gave a response time of approximately 50 ms, below the 200 ms maximum delay stipulated in literature [Farina et al. 2014].

EMG Distribution Estimation

EMG signals are stochastic, meaning there is some underlying probability distribution governing the likelihood of observing sampled EMG data. For muscle activity data sampled from the forearm, three main factors play a part in this: the position of the electrode on the forearm, the intensity of the signal, and the time at which the signal was generated. The position on the forearm is the two-dimensional position along the axis of—and around the circumference of—the forearm. Muscles in the forearm are approximately aligned with its axis, meaning an EMG signal varies by a relatively small amount along the bulk muscles of the forearm compared to circumferential position on the forearm, which is directly related to which muscles’ activities are being detected. The intensity of the EMG signal is limited

by the detection range possible with the chosen electrodes, truncating the signal between a minimum I_l and maximum I_u value. Finally, over a suitable time window, EMG signals can be assumed to be stationary [Nazmi et al. 2017], and are therefore independent of time. Using this information, the probability of observing a sample at a particular intensity, position on the forearm, and time, can be reduced to a two-dimensional probability of observing a sample of a particular intensity I , at a circumferential position θ on the forearm. In this sense, the received signal exists on a cylinder that wraps around the forearm, capped between a minimum and maximum intensity by the sensing limits of electrodes, shown in Fig. 3.5.

Kernel Density Estimation (KDE) was used to estimate the underlying probability distribution that produces observed EMG signals. The intensity dimension, I , is limited by the minimum and maximum sensing limits of the electrodes, so a truncated Gaussian kernel was used:

$$p(I|\mu, \sigma, I_l, I_u) = \text{TrG}(I|\mu, \sigma, I_l, I_u) \propto \frac{\exp\left(-\frac{(I-\mu)^2}{2\sigma^2}\right)}{\Phi\left(\frac{I_u-\mu}{\sigma}\right) - \Phi\left(\frac{I_l-\mu}{\sigma}\right)}, \quad (3.4)$$

where $\Phi(a) = \frac{1}{2}(1 - \text{erf}(-\frac{a}{\sqrt{2}}))$. An example of the truncated nature of this kernel is shown in Fig. 3.6, Left. The circumferential position dimension, θ , is wrapped, so a von Mises distribution, also known as a circular Gaussian, was used:

$$p(\theta|\nu, \kappa) = \text{vM}(\theta|\nu, \kappa) \propto \exp\left(\kappa \cos(2\pi(\theta - \nu))\right), \quad (3.5)$$

where the circumferential position was scaled $\theta - \nu$ such that a full rotation around the forearm was equal to 1.0. An example of the wrapped nature of this kernel is shown in Fig. 3.6, Middle.

The two dimensional kernel K_h formed from the outer product of the individual one dimensional kernels was used for kernel density estimation. After the estimate was produced (an example is shown in Fig. 3.6, Right), it was normalised to produce a valid probability distribution:

$$p(x) = \text{KDE}(x, |\mathbf{x}_{c=1:C}) = \frac{1}{C} \sum_{c=1}^C K_h(x - x_c). \quad (3.6)$$

The kernel density estimate was rapidly updated by maintaining a rolling dataset of 20 samples from which the estimate is calculated. For each set of d incoming samples, the components of the d oldest samples in the dataset were subtracted from the estimate, and the d new samples' components added. This was found to be considerably faster than recalculating the entire estimate, which had a complexity of $\mathcal{O}(DM)$, where D is total size of the rolling dataset and M is the number of points at which the new estimate is computed. Updating only d samples has a complexity of $\mathcal{O}(2dM)$, which, given $d \ll D$, resulted in a large saving in computation.

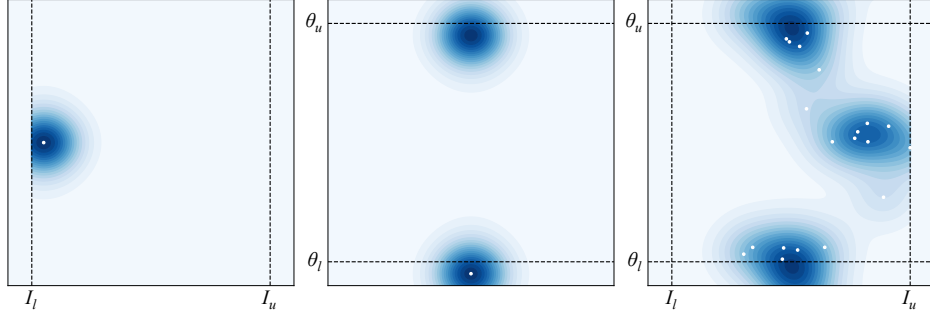


Figure 3.6: Kernel density estimation in cylindrical data space. Illustrative two-dimensional kernel density estimation plots, darker blue indicates a higher estimated probability, white points indicate observed data. The horizontal axis represents the intensity of observed samples, I , and the vertical axis represents the circumferential position of the sample around the forearm, θ . Left: example of the truncated Gaussian kernel used in the linear dimension. Middle: example of the von Mises kernel used in the wrapped dimension. Right: example generated kernel density estimate from multiple randomly sampled points.

3.4.2 Comparing Muscle Activity Data via a Distance Metric

After the distribution responsible for producing the observed EMG signal has been computed, it must be compared against reference distributions of known actions in order to classify the desired action of the user. A suitable method to compare two distributions is to calculate the distance between them, known as the Wasserstein distance.

The Wasserstein distance was calculated by first drawing n samples from two distributions: $X = \{\mathbf{x}_1, \dots, \mathbf{x}_n\} \sim p_X(I, \theta)$, and $Y = \{\mathbf{y}_1, \dots, \mathbf{y}_n\} \sim p_Y(I, \theta)$. A kernel density estimate forms a complex distribution that is typically difficult to sample from if evaluating the complete probability density function is required. A much more efficient way (illustrated in Fig. 3.7) to draw a sample $x_j = [I_j, \theta_j]^T$ from a KDE was to draw a sample $x_j^0 = [I_j^0, \theta_j^0]^T$ from the kernel distribution K_h (Fig. 3.7, upper middle), and randomly assign it to component $x_c = [I_c, \theta_c]^T$ with uniform probability (Fig. 3.7, lower middle):

$$x_j = x_j^0 + x_c, \quad x_j^0 \sim K_h, \quad c \in \{1, \dots, C\}. \quad (3.7)$$

Since each sample was comprised of circumferential position and intensity, $\mathbf{x}_i = [I_i^{(x)}, \theta_i^{(x)}]^T$ and $\mathbf{y}_j = [I_j^{(y)}, \theta_j^{(y)}]^T$, the distance $d_{i,j}$ between them was defined as the geodesic on the cylindrical space introduced previously:

$$d_{i,j} = \sqrt{(I_i^{(x)} - I_j^{(y)})^2 + a(\theta_i^{(x)}, \theta_j^{(y)})^2}, \quad (3.8)$$

where $a(\theta_i^{(x)}, \theta_j^{(y)})$ refers to the minimum unit circumferential distance between points $\theta_i^{(x)}$ and $\theta_j^{(y)}$, defined as $a(\theta_i^{(x)}, \theta_j^{(y)}) = ((\theta_i^{(x)} - \theta_j^{(y)} + 0.5) \bmod 1) - 0.5$.

The Wasserstein distance is a distance metric between two distributions, in which the optimal transport plan to transform one distribution to the other is found. The q -th Wasserstein distance

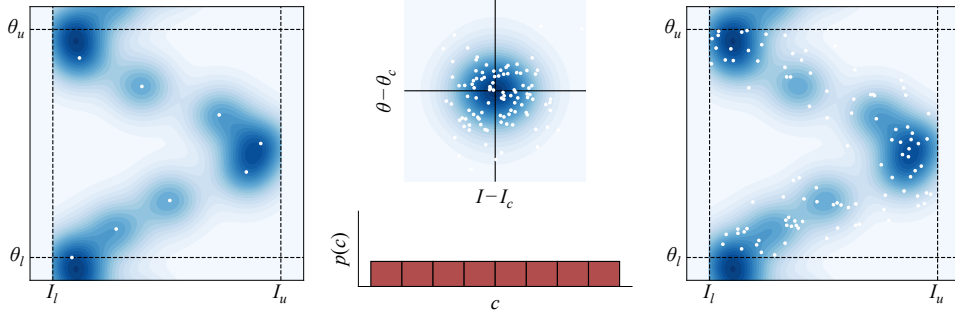


Figure 3.7: Sampling from a kernel density estimate (KDE) in cylindrical data space. Illustrative example showing sampling from a kernel density estimate. Left: Original KDE and component data. Upper Middle: intensities sampled from the two dimensional kernel making up the KDE. Lower Middle: component assignment probabilities as a uniform distribution. Right: Data resampled from the KDE to obtain a more representative data sample.

between probability distributions p_X and p_Y is defined as:

$$W_q(p_X, p_Y) = (\inf \mathbb{E}[d(X, Y)^q])^{1/q}, \quad X \sim p_X, Y \sim p_Y, \quad (3.9)$$

where $d(X, Y)$ is a distance metric between random variables X and Y . In this work, given individual samples from X and Y , $x_i = [I_i^{(x)}, \theta_i^{(x)}]^T$ and $y_j = [I_j^{(y)}, \theta_j^{(y)}]^T$, the cylindrical space on which muscle activity exists was used as the basis of the distance metric:

$$d(x_i, y_j, \beta) = \sqrt{(I_i^{(x)} - I_j^{(y)})^2 + \alpha(\theta_i^{(x)}, \theta_j^{(y)}, \beta)^2}, \quad (3.10)$$

where $\alpha(\theta_i^{(x)}, \theta_j^{(y)})$ is the minimum unit circumferential distance between points $\theta_i^{(x)}$ and $\theta_j^{(y)}$ scaled by β , defined as $\alpha(\theta_i^{(x)}, \theta_j^{(y)}, \beta) = \beta(((\theta_i^{(x)} - \theta_j^{(y)} + 0.5) \bmod 1) - 0.5)$. This distance in cylindrical space is illustrated in Fig. 3.8. Scaling the distance by β allowed the Wasserstein distance calculation to favour one dimension over the other; in the context of the controller presented in this chapter, this allowed the controller to favour intensity changes over circumferential position changes (which was useful when robustness to muscle weakness is required), or to favour circumferential position changes over intensity changes (which was useful when robustness to electrode position changes was required). In this work, β was set to 3.0 empirically.

As detailed in [Rubner et al. 2000], the Wasserstein distance between p_X and p_Y aims to find a flow $\mathbf{F} = [f_{i,j}]$, between each sample $\mathbf{x}_i$ and $\mathbf{y}_j$. When n samples are drawn from each distribution, the flow is that which minimises the following optimal transport cost:

$$\text{WORK}(X, Y, \mathbf{F}) = \sum_{i=1}^n \sum_{j=1}^n d_{i,j} f_{i,j}, \quad (3.11)$$

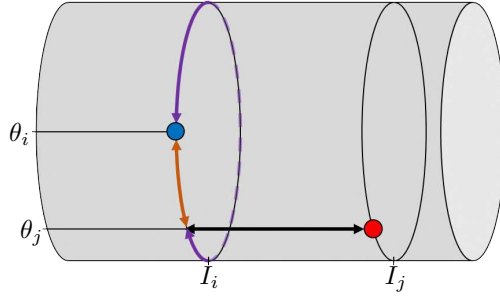


Figure 3.8: Measuring the distance between samples in cylindrical space. The distance between two points, $[I_i, \theta_i]^T$ and $[I_j, \theta_j]^T$, sampled from a cylindrical space with linear dimension I and circumferential dimension θ . Alternative options to calculate the circumferential distance between the points are shown in orange and purple, respectively.

subject to:

$$f_{i,j} \geq 0 \quad 1 \leq i \leq n, \quad 1 \leq j \leq n \quad (3.12)$$

$$\sum_{j=1}^n f_{i,j} \leq 1 \quad 1 \leq i \leq n \quad (3.13)$$

$$\sum_{i=1}^n f_{i,j} \leq 1 \quad 1 \leq j \leq n \quad (3.14)$$

$$\sum_{i=1}^n \sum_{j=1}^n f_{i,j} = n. \quad (3.15)$$

When the optimal flow has been found by solving the optimal transport problem, the Wasserstein distance is the normalised optimal work:

$$W_2(p_X, p_Y) = \frac{\sum_{i=1}^n \sum_{j=1}^n d_{i,j} f_{i,j}}{\sum_{i=1}^n \sum_{j=1}^n f_{i,j}}. \quad (3.16)$$

For a multi-dimensional distribution, the number of calculations performed to solve the optimal transport problem rapidly grows with number of samples beyond computational feasibility. To reduce computational complexity, Sinkhorn divergences were used to considerably improve calculation speed — this section is not intended to cover this approximation, and [Feydy et al. 2019] provides a good overview of the practical methods used to calculate approximations to the Wasserstein distance.

In this work, the Wasserstein distance was calculated using $n = 250$ sampled points from each density estimate using the Python package ‘GeomLoss’ [Feydy et al. 2019]. This value was chosen to ensure a representative sample was drawn from each distribution such that the calculated Wasserstein distance was consistent, while balancing speed of computation.

An illustrative example of computing the Wasserstein distance between two sets of samples can be seen in Fig. 3.9, showing offsets in the intensity dimension (left), circumferential direction (middle), and both dimensions (right).

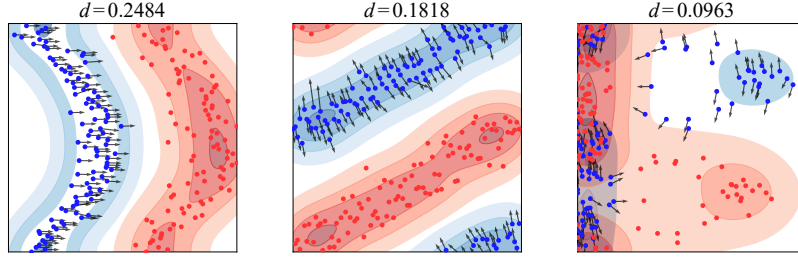


Figure 3.9: Illustrative example of the computed Wasserstein distance between two distributions in cylindrical data space. The Wasserstein distance is computed from datapoints resampled from two distributions (here coloured blue and red). Black arrows show the direction of point mass correspondences between sampled data from each distribution that produce the optimal transport solution. Left: offset in the linear intensity dimension. Middle: offset in the wrapped circumferential position dimensions. Right: ‘toy’ muscle activity data showing two independent muscles activating, while others remain inactive.

3.4.3 Distance-Based Discrete Control

To achieve discrete control, a distance-based classification rule was used to select the reference that was closest to the live distribution of EMG signals. Given R pre-recorded references, candidate reference a was selected:

$$a = \operatorname{argmin}\{W_2(p_X, p_{Y_1}), \dots, W_2(p_X, p_{Y_R})\}. \quad (3.17)$$

Given a set of reference joint angles of the prosthesis $Q = [\mathbf{q}_1, \dots, \mathbf{q}_R]^T$, the candidate action was only processed as the command action $\mathbf{q}$ at control step $k + 1$ if it fell below a distance threshold d_l :

$$\mathbf{q}(k + 1) = \begin{cases} \mathbf{q}_a & W_2(p_X, p_{Y_a}) < d_l \\ \mathbf{q}(k) & \text{otherwise} \end{cases}. \quad (3.18)$$

Because calculating the Wasserstein distance involved randomly sampling from each KDE, the distance between two identical distributions was not exactly zero. The value of the distance threshold d_l was chosen in order to ensure that the distance between two distributions was statistically significant. That is, knowing the variance of the kernel distribution making up the KDE, the distance threshold is calculated such that the p value of the one-tailed student’s t -test score at this distance is less than 0.05 when two identical, but offset, sets of samples are used (i.e. when the Wasserstein distance between the two distributions is minimum). An illustrative example of discrete control via the Wasserstein distance is shown in Fig. 3.10, and a summary of the distance-based controller shown in Fig. 3.11.

3.4.4 Controller Evaluation Methods

For this controller, the OLYMPIC hand [Liow et al. 2020] was also used as a test platform, with the addition of a modular powered forearm that was able to pronate and supinate the hand (shown in Fig. 3.12). To allow the OLYMPIC hand to be worn by participants with upper limb difference,

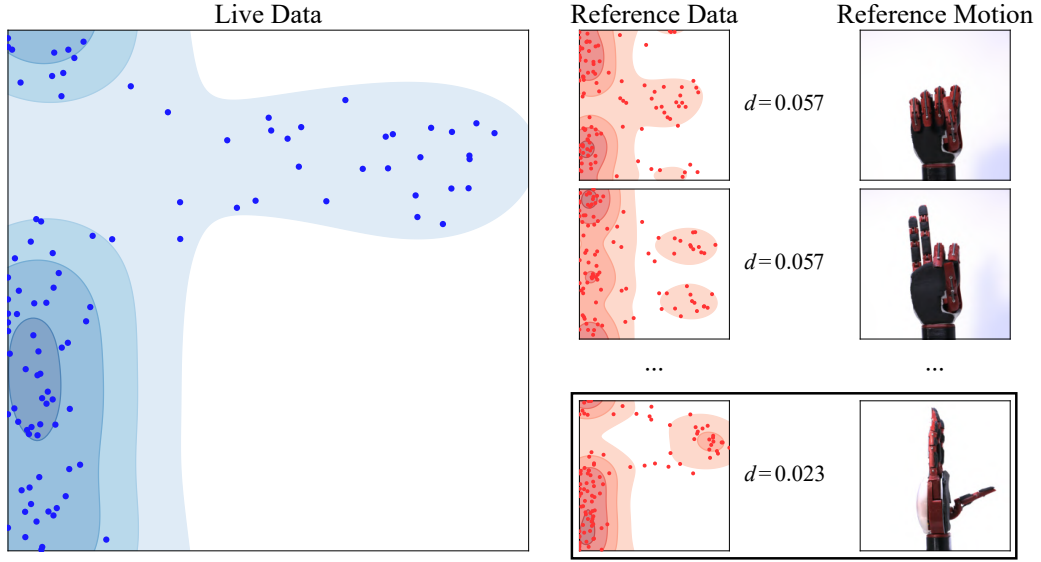


Figure 3.10: Illustrative example of the discrete control process. At each control step, the Wasserstein distance between the live data and each of the reference data are computed. If the Wasserstein distance falls below a threshold this reference is accepted as the correct motion.

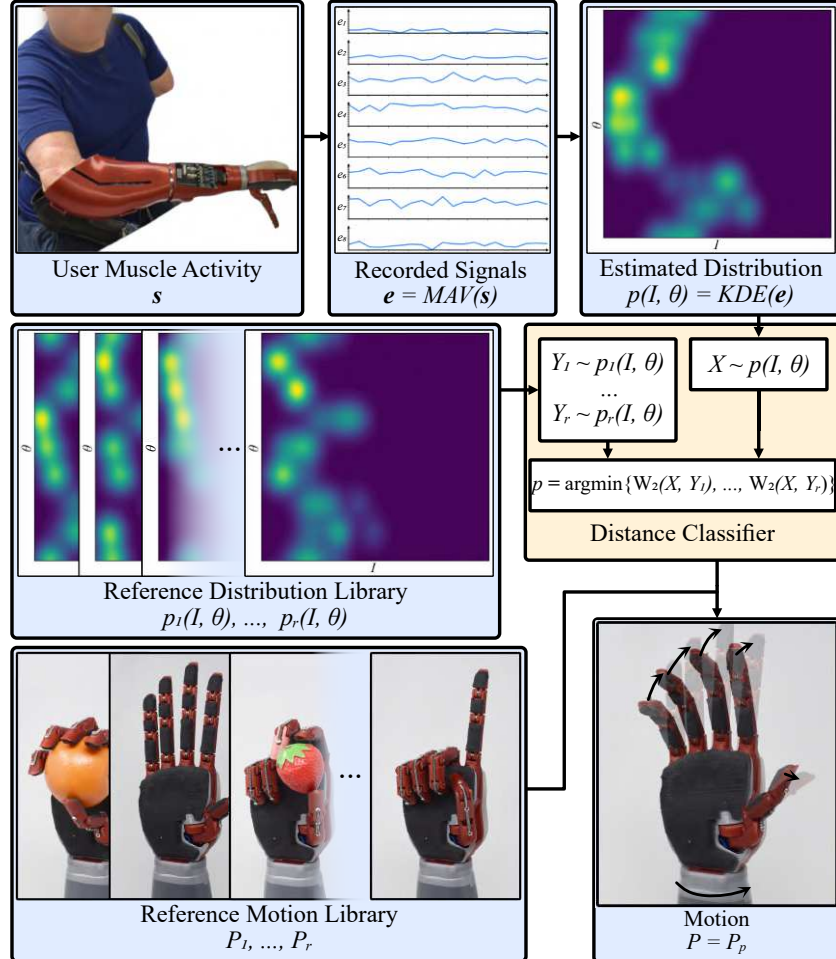


Figure 3.11: Summary diagram of the controller presented in this work. Electromyography signals were collected from the forearm of the user via surface electrodes, then the underlying distribution producing the observed signals was estimated using kernel density estimation. The Wasserstein distance was computed between the estimated distribution and a set of reference distributions to determine the desired motion of the prosthetic hand.

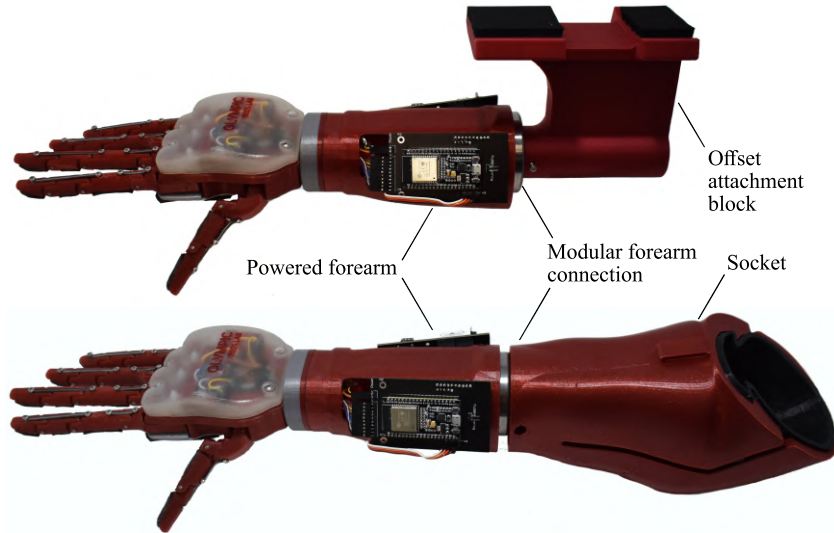


Figure 3.12: The OLYMPIC hand with modular powered forearm. Top: forearm connected to an offset attachment block for participants without upper limb difference. Bottom: forearm connected to a custom socket for the participant with upper limb difference.

the microcontroller used in Section 3.3 was mounted off-prosthesis, making the forearm shorter and allowing space for a custom 3D printed socket.

Ten participants without ULD and one participant with ULD (a body-powered prosthesis user) were recruited to take part in this study. A pilot study was conducted in which participants were asked to record reference distributions corresponding to the six prehensile grips identified in the Southampton Hand Assessment Procedure [Light et al. 2002]: lateral, power, tripod, tip, extension, spherical, as well as five common actions used in prosthetic hand control: wrist flexion (close hand), wrist extension (open hand), rest, pronate hand, supinate hand. To build a reference library, reference distributions were iteratively appended to the library in order of minimum distance to the existing library, after starting with the reference distribution with the greatest average distance from all other references. As seen in Fig. 3.13, as more references were added to the library, the minimum distance between them decreased, until it falls below the minimum detection threshold. The detection threshold was calculated based on the mean distance between two identical distributions (which was non-zero due to random sampling when computing the Wasserstein distance) plus two standard deviations. If the distance between two references was below this threshold it was not possible to discriminate between them with statistical confidence. The minimum distance between reference distributions for the participant with upper limb difference was found to be consistently lower than for participants without upper limb difference. After normalising according to the mean and standard deviation of each set of results for participants without ULD, an uneven t -test found that this difference was statistically significant ($p < 0.01$). This highlights that references based on common actions may not always be suitable for control by actual prosthetic hand users, and references should be carefully chosen according to each individual user.

For practical experiments, 6 references were used such that recorded references would be above

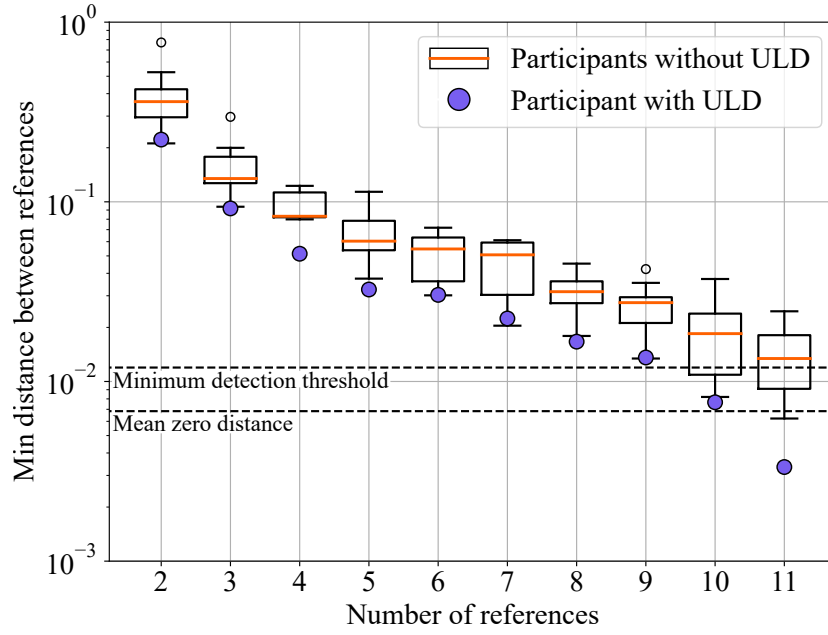


Figure 3.13: The minimum Wasserstein distance between reference distributions against number of reference distributions. References are added in descending order of minimum distance to references already in the library, starting with the reference with the greatest average distance to other references. Minimum detection threshold and mean zero distance are shown as dashed lines. Note that mean zero distance is non-zero due to random sampling.

the minimum detection threshold. This was because users were rarely able to perfectly recreate a pattern of muscle activity, and physiological factors such as fatigue and quality of the electrode-skin contact can degrade recorded signals over time; a myoelectric controller should be robust to this. The 6 reference actions used in this work were: 1. rest, 2. wrist flexion, 3. wrist extension, 4. tripod pinch, 5. supinate hand, and 6. pronate hand. Note that these references did not necessarily correspond to the optimal 6 references identified from the 11 actions trialled in the pilot study, rather these were the references that correspond to the desired motions of the prosthesis. For the participant with upper limb difference, it was found that actions congruent to the desired motion of the prosthesis were not distinguishable by the controller, corroborating the results of the pilot study. To handle this, the controller was calibrated with the following actions, which were found to produce distinct patterns of muscle activity; rest, pronate hand, supinate hand, power grip, thumb opposition, and pinky finger flexion.

After initially recording the six reference actions to estimate their starting distributions, participants were asked to perform ten repetitions of each action within a five-second window in a dictated random order, during which time the classification rate of the controller was monitored. Participants were allowed a maximum of three attempts at this task, after which the performance of their final attempt was recorded. During each attempt no feedback was available to the participant, only the notification of the next action to perform. After a complete attempt, participants were able to view their performance in order to make a decision whether to recalibrate the controller and repeat the task. Participants were then given one hour to practice controlling the hand, during which time all items

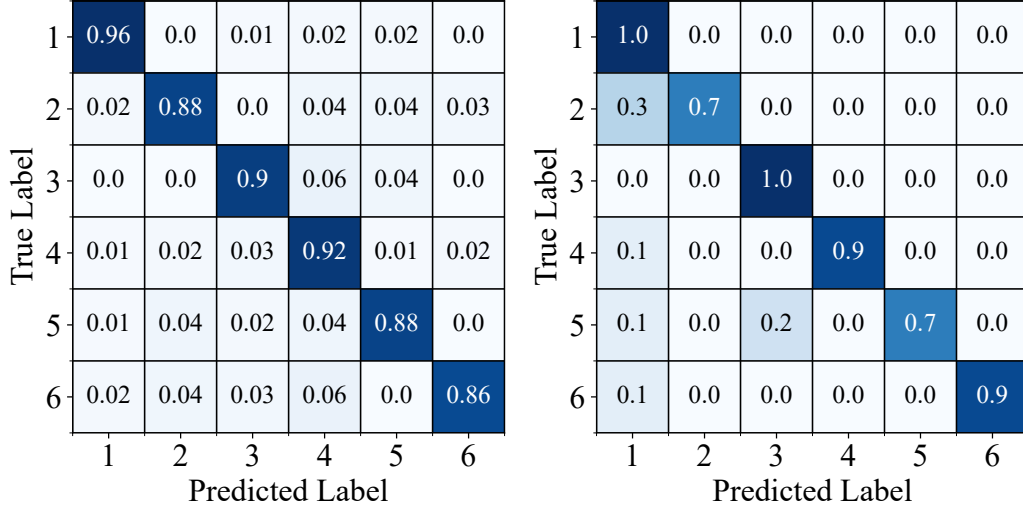


Figure 3.14: Left: Average confusion matrix across ten participants without upper limb difference normalised across each true label (1: *rest*, 2: *wrist flexion*, 3: *wrist extension*, 4: *tripod*, 5: *supinate hand*, and 6: *pronate hand*). Right: Confusion matrix for the participant with upper limb difference also normalised (1: *rest*, 2: *supinate hand*, 3: *pronate hand*, 4: *power grip*, 5: *thumb opposition*, and 6: *pinky finger flexion*).

used in subsequent dexterity tests were available for practice. After the practice period, participants completed the Jebsen-Taylor Hand Function Test [Jebsen et al. 1969], chosen because it required a mixture of fine and coarse manipulation skills at varying degrees of wrist pronation and supination. Participants were able to recalibrate the controller at any point during the training period and during the JTHFT.

The recruiting of participants without ULD and with ULD to experiments performed in this chapter was granted ethical approval by the Imperial College London Research Governance and Integrity Team (RGIT), Science Engineering and Technology Research Ethics Committee (SETREC) number 21IC6716 and Imperial College Research Ethics Committee (ICREC) number 21IC7227, respectively. Written consent was obtained from all participants prior to taking part in the study.

3.4.5 Controller Evaluation Results

To measure the ability of the controller to classify user muscle activity, ten participants without ULD were asked to perform ten repetitions of the six reference actions. Given a maximum of only two calibrations, users were able to achieve an average accuracy of 89.9%, comparable with existing deep learning-based controllers [Yang et al. 2022; Côté-Allard et al. 2019]. The average confusion matrix corresponding to this task is shown in Fig. 3.14 Left. As seen, reference 4, tripod grip, elicited the most type I (false positive) errors, which are most prevalent when users attempt to perform reference 3, wrist extension, and 6, pronate hand. This is likely due to overlap in the muscle groups that produce these actions, and variance when users repeatedly perform actions; users may not perform actions identically every time, meaning a reference distribution generated from a single sample of data may not fully represent that action. It was observed that there may be a relationship between

the distance between reference distributions and classification rate; for example, if two references were close together then it was more likely that the controller would misclassify these two references. Fig. 3.14 Right shows the confusion matrix produced by participant with ULD, who achieved an average accuracy of 86.7%. In this case, reference 1, rest, elicits the most false positive errors. This could be due to weaker muscles present in the participant with upper limb difference's residual limb, which were not used on a regular basis when operating a body-powered prosthesis.

The results of the Jebsen-Taylor Hand Function Test can be seen in Fig. 3.15. All participants were able to complete each task, although picking and placing small objects (J3) required on average more time than the JTHFT protocol's 120 s maximum time limit. In general, it can be observed that task completion required greater time using the OLYMPIC hand than the participant with upper limb difference's current body powered prosthetic hand. This time increase can be resolved into four primary sources; user expertise, classifier latency, motion latency, and mechanical features.

User expertise refers to the level of practice a user had experienced with each prosthesis. The participant with upper limb difference used a body powered prosthesis for day to day tasks, so could be considered an expert user. With the OLYMPIC hand, all users could be considered novice users, because they had only been given one hour to practice. The effect of user expertise can be seen in the writing (J1) and feeding (J4) tasks; the participant with upper limb difference outperformed participants without upper limb difference when using the OLYMPIC hand. These tasks were accomplished with a static grip in the same way that a body-powered prosthesis grasps an object.

Classifier latency is the time period between a user attempting to produce muscle activity required to perform a desired motion and the point in time at which the classifier successfully classifies the muscle activity produced. In the controller presented in this work, references were recorded of muscles at steady state, so users must match this. Identifying exactly when a user begins to attempt a motion is difficult, but — from observations made during these experiments — can range from 0.25 s to 2 s depending on the participant and the motion which they are attempting. Classifier latency dominates tasks involving large objects (J6 and J7), and is not present in body-powered prostheses.

Motion latency is the time period between muscle activity being successfully classified and the prosthetic hand completing the desired motion. This depends on the motion and any object the hand interacts with. Since the controller used in this work was discrete, i.e., it moved between fixed discrete poses, motion latency was relatively high. Motion latency makes up a significant proportion of the time increase observed between the body powered prosthesis and the myoelectric prosthesis, particularly when grasping small objects (J2, J3, and J5). The body powered prosthesis was able to remain in a semi-closed state making grasping much quicker than fully opening and closing the OLYMPIC hand.

Certain mechanical features of the OLYMPIC hand led to observed time differences in some tasks. The tasks which exhibited the largest increase in time taken to complete were picking and placing small objects (J3) and stacking checkers (J5). As described in Chapter 2, each finger of the OLYMPIC hand

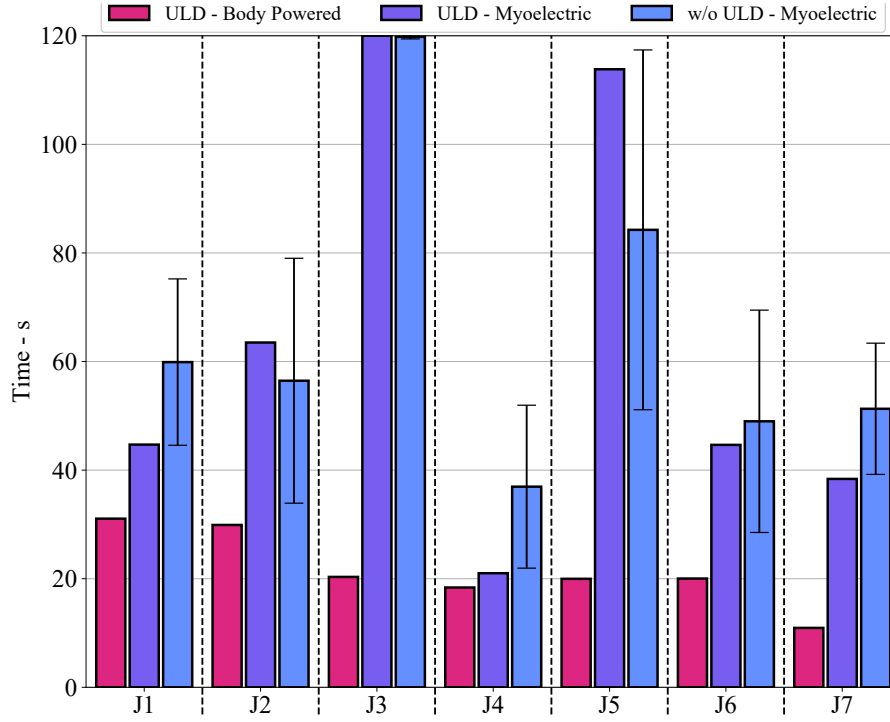


Figure 3.15: Results of the Jebsen-Taylor Hand Function Test for ten participants without upper limb difference and one participant with upper limb difference. ULD: participant with upper limb difference, w/o ULD: participants without upper limb difference. J1: Writing, J2: Simulated page turning, J3: Small objects, J4: Simulated feeding, J5: Stacking checkers, J6: Large, light objects, J7: Large, heavy objects.

is underactuated. The equilibrium between the extension springs mounted on the dorsal side and the flexion tendon that runs within them governing the path taken during closing if motion is unrestricted. If motion was hindered in any way, this equilibrium was disrupted, and the finger deviated from its path. It should be noted that this made grasping small objects challenging in practice, since all fingers used in the grasp were required to move unhindered to the grasping posture for a repeatable, precise grasp. So, although users were able to perform the correct patterns of muscle activity required to close the hand in tripod grip and open the hand again, many more attempts were required to successfully grasp each object. Furthermore, a time difference on the writing (J1) and simulated feeding (J4) tasks was observed between the results of the participant with ULD using their body powered prosthesis compared to results of both the participant with ULD and participants without ULD performing this task with the OLYMPIC hand. This increase is due to the OLYMPIC hand having soft pads located on the palmar side of the hand, which means that a grasped object is able to move slightly, hindering static tasks.

3.5 Conclusions

In this chapter, two key methods of advancing discrete control were presented: expanding the control and computational capabilities of prosthetic hands, and reducing user data requirements for controller calibration and setup.

The control and computational capabilities of the OLYMPIC hand were expanded via the addition of a microcontroller and various sensors, allowing precise control of each finger, and the onboard training of a usable machine learning-based controller was demonstrated from a relatively small amount of data collected from individual users. By evaluating the controller both on training data and during roll-out, the effectiveness of the modified prosthesis was demonstrated.

The concept of minimising user data required for calibration was explored further by creating a discrete controller that relied on a single snapshot of EMG for each reference action. By creating a two-dimensional space that captured the relationship between spatial positioning of electrodes and the intensity of their corresponding EMG signals, muscle activity at two points in time could be directly compared. The controller was evaluated in terms of inter-reference distance, roll-out accuracy, and performance on the Jebsen-Taylor Hand Function Test, providing insights into factors that positively and negatively influence user performance, informing further research in this thesis.

This chapter has identified key shortfalls in emerging discrete control techniques and possible methods to address them. Focusing on improving the computational power of prostheses and developing controllers that rely on minimal user data are two steps towards making advanced discrete control accessible to users who may benefit from it.

Chapter 4

Achieving Continuous Control

This chapter is based on the work presented in:

Digby Chappell, Zeyu Yang, Angus B. Clark, Alexandre Berkovic, Colin Laganier, Weston Baxter, Fernando Bello, Petar Kormushev, and Nicolas Rojas (2024b). “Combining multi-modal feedback with continuous control improves performance and psychological embodiment in prosthetic hand users”. In: *Scientific Reports (Under Review)*

Alexandre Berkovic, Colin Laganier, **Digby Chappell**, Thrishantha Nanayakkara, Petar Kormushev, Fernando Bello, and Nicolas Rojas (May 2022). “A Multi-Modal Haptic Armband for Finger-Level Sensory Feedback from a Prosthetic Hand”. In: *Haptics: Science, Technology, Applications, EuroHaptics*. Hamburg: Springer, pp. 138–146

Continuous myoelectric controllers seek to modulate the output of a myoelectric control system continuously, allowing a user to precisely command multiple degrees of freedom of their prosthesis in a way that more closely resembles human hand motion than traditional or discrete controllers. However, an open loop continuous controller requires constant attention from the user to operate, and therefore closing the control loop via haptic devices may be beneficial. This chapter explores a method of achieving closed-loop continuous control of myoelectric prosthetic hands via non-invasive methods, and the physical (task performance) and psychological (task load and psychological embodiment) effects of this control method on users. Specifically, a continuous control extension of the Wasserstein distance-based controller developed in Chapter 3 and a haptic feedback armband capable of rendering 15 proprioceptive sensory percepts to close the feedback loop are presented.

4.1 Introduction

Prosthetic hands, in general, exist to restore the lost function of the hand or arm of a user who has an upper limb difference, be it congenital or acquired from trauma. In order to truly restore this functionality, prosthetic hands should not only take the form of a human hand, but should also be able

to be controlled in a way that mimics a human hand. However, human dexterity is a sophisticated coupling between motor and sensory neural pathways, culminating in a manipulation system that dwarfs even the best robotic hands in terms of functionality [Sobinov and Bensmaia 2021]. Although some robotic hands approach the mechanical complexity of their human counterpart [Kim et al. 2021; Tuffield and Elias 2003], the majority of prosthetic hands offer between 1 and 7 controllable degrees of freedom [Liow et al. 2020; Cho et al. 2022; Mohammadi et al. 2020; Weiner et al. 2018; Laffranchi et al. 2020]. These are generally arranged to control finger flexion and, in some cases, a secondary thumb or wrist rotation. With cost, space, and weight constraints limiting design [Belter et al. 2013], it remains unlikely that prosthetic hands will approach the full mechanical functionality of human hands in the near future. The challenge, therefore, is how to control the available DOFs of a prosthesis in the best possible way.

As discussed in 3, most common electromechanical prosthesis control method is to use pattern recognition to classify muscle activity, recorded via electromyography, into predefined actions, without providing any sensory feedback to the user. Improving accuracy and increasing the number of actions have been the focus of research dating back to the 1960s [Finley and Wirta 1967; Almström et al. 1981; Hudgins et al. 1993], yet user rejection rates and dissatisfaction have remained consistently high [Kyberd et al. 2007; Pylatiuk et al. 2007; Østlie et al. 2012; Salminger et al. 2020]. Furthermore, in almost all tasks, myoelectric prostheses are outperformed by dramatically simpler body-powered prostheses [Blue Godfrey et al. 2017; Resnik et al. 2020] (seen also in chapter 3). This is because body-powered prostheses are operated continuously with minimal latency and provide feedback to the user [Smit and Plettenburg 2010; Smit et al. 2012; Antfolk et al. 2014], in what is known as closed-loop continuous control (CLCC). Achieving CLCC of multiple DOFs of myoelectric prostheses may be a large step towards restoring dexterity to users.

In this chapter, the state of the art in non-invasive methods is extended with a novel closed-loop continuous prosthetic hand controller that can modulate three controllable DOFs of the OLYMPIC hand [Liow et al. 2020]: power grip (DOF I), wrist pronation/supination (DOF II), and tripod grip (DOF III). To close the control loop, a haptic feedback armband is introduced, which renders complete proprioceptive feedback of the position and force of each finger, and wrist position to the user via 15 actuators, while maintaining a wearable form. Fig. 4.1 summarises this closed-loop continuous controller. 28 participants without ULD formed four groups: open-loop discrete control (OLDC), closed-loop discrete control (CLDC), open-loop continuous control (OLCC), and closed-loop continuous control. As case studies, 10 participants with ULD used the CLCC setting. The controller was evaluated holistically: participants completed isolated control and sensory tasks, contextual dexterity assessments, and questionnaires on task load and embodiment. Finally, each participant with ULD completed a post-study interview to better understand their questionnaire results, providing detailed insights into potential causes for rejection and acceptance of a prosthesis.

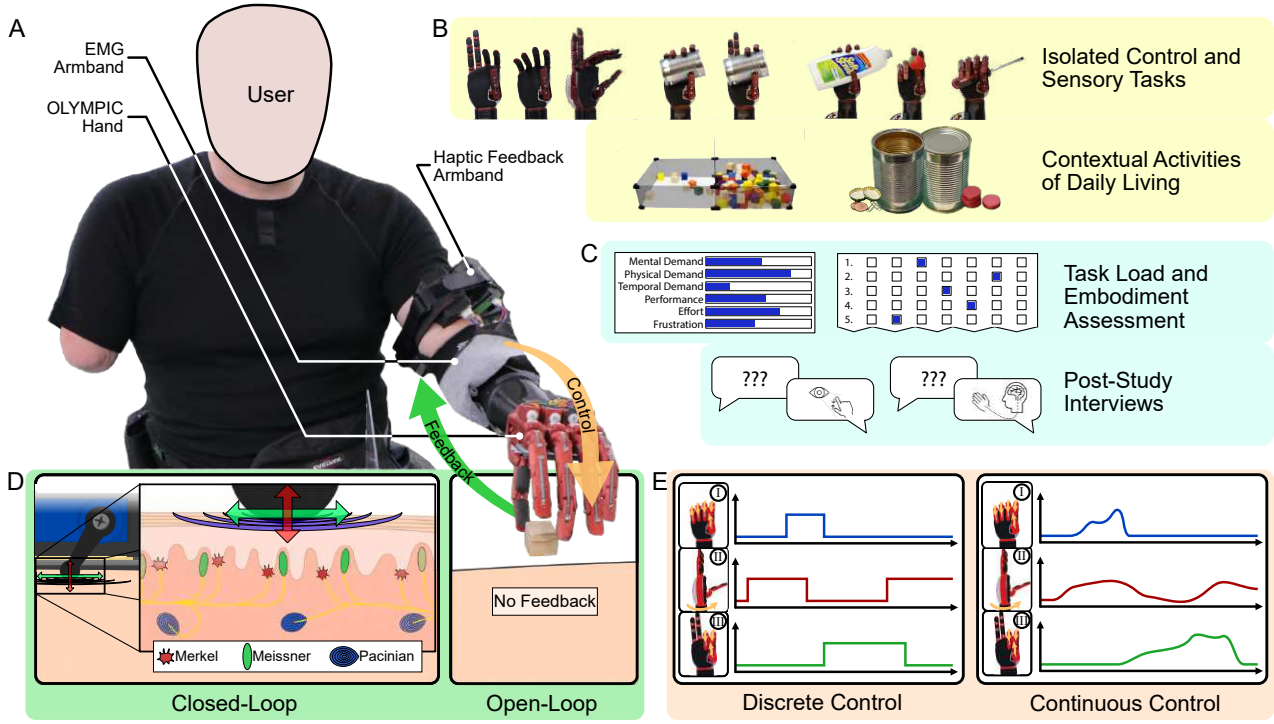


Figure 4.1: Non-invasive closed-loop continuous control achieved with surface electrodes and a haptic feedback armband. (A) A participant operating the OLYMPIC hand with the closed-loop continuous controller. (B) Physical performance evaluations. Isolated control tasks: position matching, force matching. Isolated sensory tasks: object identification. Contextual activities of daily living: Box and Blocks Test, Jebsen-Taylor Hand Function Test. (C) Psychological performance evaluations. Task load and psychological embodiment questionnaires, and post-study interviews. (D) Open-Loop and Closed-Loop conditions. Open-Loop: no feedback is rendered to the user. Closed-Loop: multimodal feedback is rendered to the user with a haptic feedback armband. (E) Discrete Control and Continuous Control conditions. Discrete Control: reference actions are activated with binary signals. Continuous Control: reference actions are activated with modulated signals proportionally and simultaneously.

4.2 Related Work

Achieving closed-loop continuous control of a prosthesis is a non-trivial challenge, and previous research is often limited to attempting one half of the goal; either closing the feedback loop or achieving continuous control in isolation. To overcome poor EMG signal quality and lower sensory acuity associated with the skin of a user's residual limb, many works resort to invasive surgical procedures to either implant electrodes for EMG detection [Lukyanenko et al. 2021; George et al. 2019; Brinton et al. 2020; Paskett et al. 2021] or nerve stimulation [George et al. 2019; D'Anna et al. 2019; Clemente et al. 2019; Zollo et al. 2019], or for reinnervation of neural pathways [Marasco et al. 2021]. While these studies show strong results, controlling up to 6 DOF [George et al. 2019], as case studies of one [George et al. 2019] or two [D'Anna et al. 2019; Marasco et al. 2021] participants they are limited in how applicable they may be for a wider population. Moreover, the uptake of such methods is currently restricted due to the costly and experimental nature of its associated surgical procedures. With implanted technology, there is a risk that the small population of prosthesis users become reliant on commercial technology where there is no guaranteed long-term support or protection from

obsolescence. Non-invasive techniques, utilising electrodes and feedback devices mounted on the skin’s surface, may therefore present the most feasible route to closed-loop continuous control reaching a wider population. However, results of these techniques are much more limited, controlling fewer DOFs [Hahne et al. 2018; Dyson et al. 2018; Dyson et al. 2020] and rendering few modalities of feedback to fewer feedback sites [Antfolk et al. 2013; Gu et al. 2021; Cha et al. 2022; Abd et al. 2022]. Existing works exploring CLCC using non-invasive technology have presented a single controlled DOF and single modality of feedback [Clemente et al. 2016], or even just a single finger [Vargas et al. 2021]. One of the most advanced examples of non-invasive CLCC comes from the work of Abd et al., which demonstrated CLCC of 2 DOF of a robot arm-mounted, sensor-equipped robot hand [Abd et al. 2022]. However, the applicability of this technique to real prostheses is questionable due to the robot arm-mounted hand, avoiding EMG data collection difficulties of a worn prosthesis, and due to sensory feedback being rendered to the user upon known object breakage, which requires a level of knowledge about the grasped object that is unobtainable in the real world. Furthermore, studies utilising tactile feedback [Clemente et al. 2016; Abd et al. 2022] are limited in their application to currently used prostheses by the wider population, which are not equipped with tactile sensors, and are therefore limited to sensing only proprioceptive information. As such, there is significant scope for further research into non-invasive techniques to achieve proprioceptive CLCC of myoelectric prosthetic hands.

Evaluation is central in prosthetic technology; prosthetic hand control is a complex, multifaceted relationship between human and technology. Both physical and psychological factors must be considered to obtain a more complete understanding of this. Often, invasive and non-invasive studies alike evaluate a small subset of these factors, such as isolated control and sensory performance [Dyson et al. 2018; Yang et al. 2022; Rossi et al. 2019], physical task performance [Hahne et al. 2018; George et al. 2019], or user perception [Benz et al. 2016; Bekrater-Bodmann 2020]. A ‘holistic’ study examining prosthetic hand control through multiple lenses could benefit wider scientific understanding.

4.3 Continuous Control

This section presents a method of continuously modulating multiple degrees of freedom of a prosthetic hand via myoelectric control. This controller is based on the fact that EMG signals can be modelled as the output of a linear, time invariant system [Chowdhury et al. 2013], meaning that the resultant intensity of multiple active motor units is the superposition of their individual outputs. This allows us to take a generative approach to myoelectric control, rather than classifying incoming muscle activity, the problem becomes one of finding the optimal combination of independent patterns of muscle activity that form an approximate of incoming muscle activity.

4.3.1 Approximating Live Muscle Activity Data

In the context of the two-dimensional muscle activity space introduced in chapter 3, at a given circumferential position around the forearm, the live muscle activity intensity at any time can be approximated by a linear sum of the intensities of R pre-recorded independent references. The approximated muscle activity can then be updated in real time to minimise the Wasserstein distance between the approximated muscle activity and then the live muscle activity.

Conditionally Sampling from a Kernel Density Estimate

As discussed in chapter 3, to compute the Wasserstein distance, n samples must be drawn from each distribution. Because superposition of EMG signals only occurs in the intensity dimension, these samples must be drawn conditionally from the kernel density estimates (i.e. given a fixed circumferential position around the forearm). Conditionally sampling from a multivariate KDE is more complex than generally sampling from a KDE, because it requires the evaluation of the probability density function of the KDE at a given location in one or more dimensions. For the two dimensional KDE used in this work, sampling intensity I_j at a given circumferential location $\theta = \Theta$ can be achieved with a similar method to (3.7), and is illustrated in Fig. 4.2. First, evaluating the conditional probability of each component at Θ according to the Kernel used:

$$p(\theta = \Theta)_{c=1:C} = [\text{vM}(\theta = \Theta|\nu, \kappa)_1, \dots, \text{vM}(\theta = \Theta|\nu, \kappa)_C]^T. \quad (4.1)$$

These probabilities are then normalised to form the basis of a multinomial distribution (Fig. 4.2, lower middle) from which to assign intensity samples I_j^0 drawn from the kernel distribution along the intensity axis (Fig. 4.2, upper middle):

$$I_j = I_j^0 + I_c, \quad I_j^0 \sim \text{TrG}(I|\mu, \sigma, I_l, I_u), \quad c \sim \text{Mult}(c|p(\theta = \Theta)_{c=1:C}). \quad (4.2)$$

Although not used in this work, this can be easily formulated for sampling circumferential location θ_j at a given intensity $I = \mathcal{I}$, given

$$p(I = \mathcal{I})_{c=1:C} = [\text{TrG}(I = \mathcal{I}|\mu, \sigma, I_l, I_u)_1, \dots, \text{TrG}(I = \mathcal{I}|\mu, \sigma, I_l, I_u)_C]^T, \quad (4.3)$$

then sampling:

$$\theta_j = \theta_j^0 + \theta_c, \quad \theta_j^0 \sim \text{vM}(\theta|\nu, \kappa), \quad c \sim \text{Mult}(c|p(I = \mathcal{I})_{c=1:C}). \quad (4.4)$$

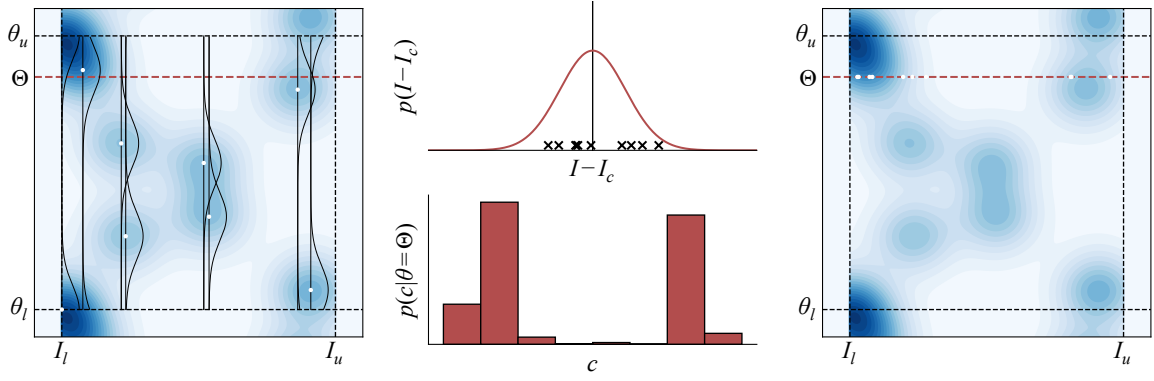


Figure 4.2: Conditionally sampling from a kernel density estimate (KDE) in cylindrical data space. Illustrative example showing conditional sampling from a kernel density estimate at the point $\theta = \Theta$. Left: Original KDE and test components, with individual component kernel probabilities along the θ axis shown. Upper Middle: intensities sampled from the truncated Gaussian kernel. Lower Middle: component assignment probabilities as a multinomial distribution computed from the component kernel probabilities at $\theta = \Theta$. Right: KDE resampled at $\theta = \Theta$.

Approximating a Target Kernel Density Estimate

In this work, continuous control is approached generatively, rather than from a discriminative approach. Continuous control is achieved by considering how to reconstruct the distribution of live EMG signals from a linear combination of reference distributions. Given that EMG signals can be modelled as the output of a linear, time invariant system [Chowdhury et al. 2013], the resultant intensity of multiple active motor units is the superposition of their individual outputs. Given that reference distributions are recorded by activating independent groups of muscles, the observed intensity of live EMG at a given circumferential position $\theta = \theta_n$ around the forearm can be approximated as a weighted linear combination of each reference intensity at that location:

$$\hat{I}\big|_{\theta=\theta_n} = \sum_{r=1}^R w_r I_r \big|_{\theta=\theta_n}, \quad (4.5)$$

where w_r is the weighting applied to reference r . Repeating this process at many circumferential positions $\Theta = [\theta_1, \dots, \theta_N]^T$ yields a series of approximate intensities that follow the conditional distribution

$$p_{\hat{I}|\theta=\Theta} = p(\hat{I}|\theta = \Theta, \mathbf{w}), \quad (4.6)$$

where $\mathbf{w} = [w_1, \dots, w_R]^T$ is the vector of weights applied to each reference. The resultant distribution, $p_{\hat{X}}$, is equal to:

$$p_{\hat{X}} = p(\hat{I}|\theta = \Theta, \mathbf{w}) p(\theta = \Theta). \quad (4.7)$$

To measure how well these weightings approximate the live data, the Wasserstein distance between the live distribution and the approximate distribution, conditionally sampled at $\theta = \Theta$, can then be

used as a loss function:

$$\mathcal{L}_W = W_2(p_X, p_{\hat{X}}). \quad (4.8)$$

The approximate distribution $p_{\hat{X}}$ is formed via the summation of many random variables (each reference intensity I_r is a random variable composed of many KDE components, each with their own intensity), meaning the resultant probability density function is the convolution of each of the corresponding probability density functions. This approximate distribution must then be sampled in order to calculate the Wasserstein distance. It is computationally infeasible to perform these calculations at every control step, so an alternative approach is considered. It is equivalent mathematically to, rather than compute the resultant probability density function then conditionally sample it, conditionally sample each reference probability density function then perform the weighted sum of these samples:

$$\hat{I}\big|_{\theta=\Theta} = \sum_{r=1}^R w_r I_r \big|_{\theta=\Theta}, \quad \hat{I} \sim p_{\hat{I}|\theta=\Theta}, \quad I_r \sim p_{I_r|\theta=\Theta}. \quad (4.9)$$

4.3.2 Distance-Based Continuous Control

With a larger reference library, it becomes increasingly easy to fall into local minima that explain the incoming muscle activity data. To avoid some of these, pairs of references that are produced by antagonistic muscle pairs can be considered. If the reference library contains references involving muscles that form an antagonistic pair, then only one reference from the pair should contribute to the resultant distribution at any time. To ensure that this is the case, a gating function is used, such that when one reference in the pair is high, the other reference is suppressed, and vice versa. The gating function chosen is an inverted sigmoid function, which outputs zero when w_i is high, and one when w_i is low:

$$g_r(w_r) = 1 - \frac{1}{1 + \exp(-k(w_r - w_0))}. \quad (4.10)$$

For a reference library that is comprised of a combination of antagonistic references and complementary references, two flagging matrices are used to identify allowable combinations of samples. The first is an antagonistic flag matrix, $A \in \mathbb{R}^{R \times R}$, which is zero-filled with unit flags at entries A_{r_1, r_2} and A_{r_2, r_1} to indicate that references r_1 and r_2 make an antagonistic pair. The second is an isolated flag matrix, $C \in \mathbb{R}^{R \times R}$, which is also zero-filled, but with unit flags at entries C_{r_1, r_1} indicating that reference r_1 is isolated and does not form an antagonistic pair with any other reference in the library. The final weight of reference r_1 is equal to:

$$\bar{w}_{r_1} = \left(C_{r_1, r_1} (1 - g_{r_1}(w_{r_1})) + \sum_{r_2=1}^R A_{r_1, r_2} g_{r_2}(w_{r_2}) \right) w_{r_1}. \quad (4.11)$$

Note that C_{r_1, r_1} is multiplied by $1 - g_{r_1}(w_{r_1})$ in order to balance the gradients of the antagonistic flag sigmoid. In vector notation where $\mathbf{g} = [g(w_1), \dots, g(w_R)]^T$:

$$\bar{\mathbf{w}} = \text{diag}(C(\mathbf{1} - \mathbf{g}) + A\mathbf{g})\mathbf{w}. \quad (4.12)$$

At each control step, the weighting of each component distribution is optimised using the gradient of the Wasserstein distance between the approximate and live distributions. To warm start the optimisation, the optimised weightings from the previous control step are used to initialise the weightings of the current control step. Convergence to an optima is not guaranteed within the control step time period; in this case the most recent weightings are taken as the solution.

To convert computed weights to an output motion, each reference is mapped to a set of prosthesis joint angles $\mathbf{Q} = [\mathbf{q}_1, \dots, \mathbf{q}_R]^T$. Complementary references are mapped to independent motions; for example, the motion of the wrist and fingers. Antagonistic references are mapped to overlapping motions such that they cannot be activated at the same time; for example, tripod grip and power grip. The target position of the prosthesis $\hat{\mathbf{q}}$ at the next control step, $k + 1$, is the weighted sum of each reference, exponentially smoothed with its current target position:

$$\hat{\mathbf{q}}(k + 1) = \alpha \sum_{r=1}^R w_r \mathbf{q}_r(k + 1) + (1 - \alpha)\mathbf{q}(k), \quad (4.13)$$

where α is the smoothing factor, chosen heuristically as 0.3. A summary block diagram of the entire continuous control process is shown in Fig. 4.3.

The most computationally intensive step in the control system is to calculate the Wasserstein distance. In the discrete controller, the Wasserstein distance must be calculated once for each reference at each control step. In the continuous controller, the distance calculation is only performed between the approximated data and the live data, however this is repeated in the inner weighting optimisation loop for each gradient descent step. In this work, a single gradient descent step is used per control step, meaning the controller is able to run at a rate of approximately 20 Hz, with higher rates expected with dedicated embedded hardware in the future.

4.4 Closed-Loop Control

Human sensory dexterity mechanisms are inherently dependent on both complex nervous arrangements and two sensory systems: namely proprioception, which tracks the motion of our hand and its muscular effort; and touch, which communicates key information on environment interactions [Sobinov and Bensmaia 2021]. With visual guidance being an imperfect surrogate for its highly intricate somatosensory complement and the fact that our motor systems are inherently coupled with our dexterity [Jiang et al. 2018; Umeda et al. 2019] the underlying necessity of a sensory feedback system for

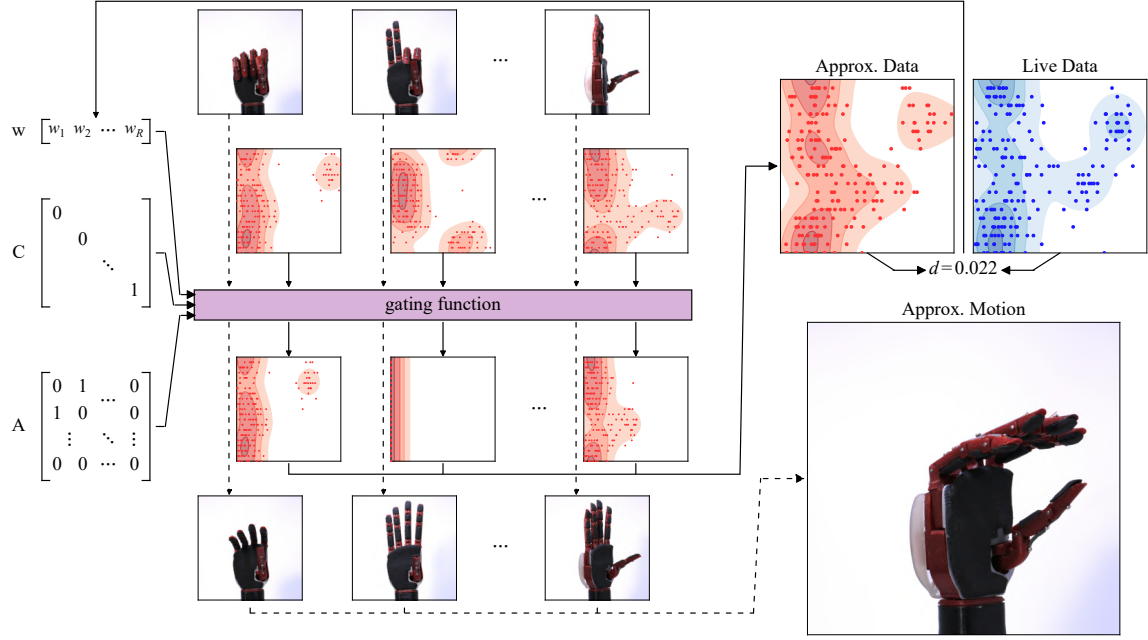


Figure 4.3: Illustrative example of the continuous control process. At each control step, an approximation of the live data is formed by performing a weighted sum of the reference data in the intensity dimension that minimises the Wasserstein distance between the approximate and live data. A gating function is used to prevent antagonistic pairs of reference data from activating simultaneously.

prosthetic hands is clear.

A multi-modal haptic feedback armband was developed, which is able to encode key aspects of proprioception, suitable for use with prosthetic hands that are not equipped with specialised sensors. In particular, three feedback mechanisms are considered: vibration, normal displacement, and tangential position, which target three corresponding cutaneous mechanoreceptors: Pacinian, Merkel, and Meissner corpuscles [Hayward 2018].

The haptic feedback armband is comprised of 5 modules — one for each finger of the prosthesis. Each module, shown in Fig. 4.4 C, renders vibration, normal displacement, and tangential position via a single probe in contact with the wearer’s skin. Inside each module are two servo motors and one vibration motor. The first servo is static, and is used to move a carriage housing the second servo and vibration motor tangentially along a rail. The probe, connected to the second servo arm, produces normal displacement feedback from the angle of the second servo, and tangential position feedback from a combination of both servo angles. The housing of the vibration motor was designed to transmit from the sliding carriage, through the second servo, into the probe.

4.4.1 Rendering Feedback to the User

The haptic armband was used to render feedback from the OLYMPIC hand using the position, θ_m measured by individual finger motor encoders, torque, τ_m , of the motors driving each finger $m = [0, \dots, 5]$, and wrist pronation/supination θ_w . In the OLYMPIC hand [Liow et al. 2020], each finger

is driven in the flexion direction by an individual motor, while springs mounted on the dorsal side of each finger drive extension.

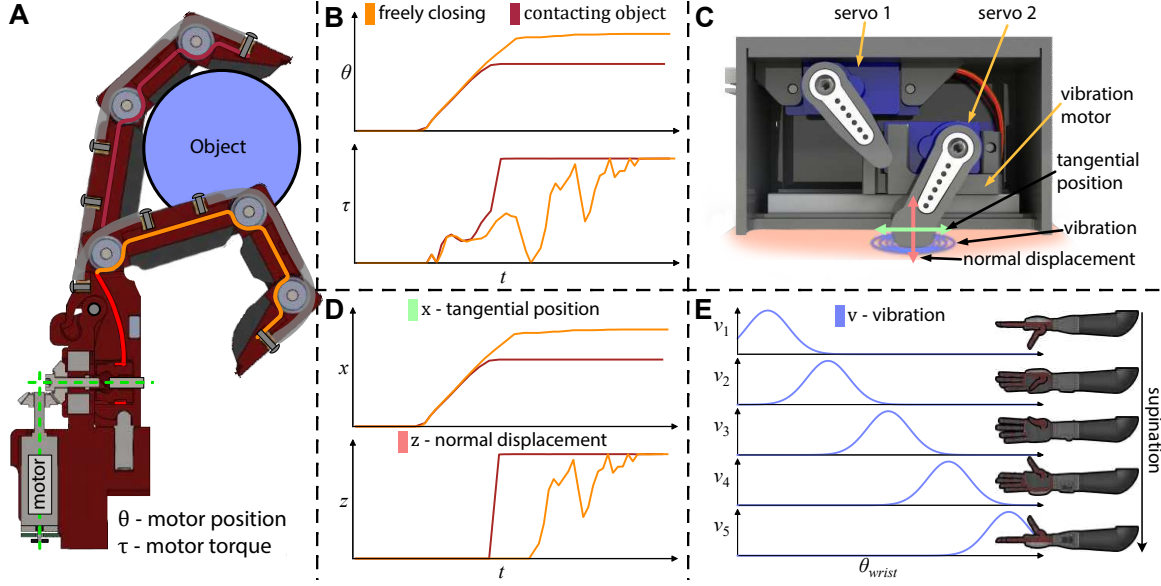


Figure 4.4: The motion of a the prosthetic hand and its corresponding sensory feedback modes. (A) A finger of the prosthetic hand shown freely closing (lighter, orange) and contacting an object (darker, purple). (B) Corresponding trajectories of the motor position θ and torque τ of the finger. (C) A section view of the corresponding haptic feedback module showing each mode of sensory feedback - tangential position (green), normal displacement (red), and vibration (blue). (D) The tangential position feedback x , representing finger position, and normal displacement feedback z , representing finger force, corresponding to the motor trajectories in (B). (E) Vibration feedback $v_1 - v_5$ of five modules, providing proprioceptive feedback of wrist pronation-supination.

The modes of feedback—tangential position, normal displacement, and vibration—render proprioceptive finger position, finger force, and wrist position, respectively, and are illustrated in Fig. 4.4. For finger f , tangential position feedback x_f was given to the user as a direct mapping of motor position θ_f :

$$x_f = \theta_f. \quad (4.14)$$

Normal displacement feedback z_f , was rendered to the user as the excess static force in the finger motor:

$$z_f = \begin{cases} \tau_f - \hat{\tau}_f(\theta_f) & \dot{\theta}_f < \dot{\theta}_l \\ 0 & \text{otherwise,} \end{cases} \quad (4.15)$$

where $\hat{\tau}_f(\theta_f)$ is the expected value of the motor force τ_f at motor position θ_f , calculated according to [Chappell et al. 2022a], and $\dot{\theta}_l$ is a motor speed threshold to prevent normal displacement from being applied prematurely.

Vibration feedback from multiple armband modules was used to provide proprioceptive position feedback from the wrist in a similar method to that presented in [Marinelli et al. 2023]. Vibration feedback rendered by each module v_f , was computed as a combination of Gaussian curves along the

pronation/supination angle of the wrist, θ_{wrist} , equally spaced by $\Delta\theta$:

$$v_f \propto \exp\left(-\frac{(\theta_{\text{wrist}} - f\Delta\theta)^2}{2(\frac{1}{3}\Delta\theta)^2}\right), \quad (4.16)$$

where the standard deviation of the Gaussian, $\frac{1}{3}\Delta\theta$, was chosen such that individual haptic modules reach their peak vibration intensity without overlap from other modules.

4.4.2 Psychometric Evaluation of the Haptic Armband

To measure the efficacy of the haptic armband, just noticeable difference (JND) was measured for normal displacement and tangential position feedback, which measures the amount of change in a stimulus that allows it to be detectable at least 75% of the time, as estimated by fitting a psychometric curve to user responses. The point of subjective equality (PSE) was also measured for the tangential position feedback, which measures the point at which users believe they have adjusted the feedback to match a given reference level. 5 users evaluated the armband in terms of JND and PSE.

As seen in Fig. 4.5 (left and middle), JND of modules located at the rear of the upper arm (modules 3,4) was significantly lower than modules at the front of the upper arm (modules 1,2,5), with median values of 0.72 mm versus 0.45 mm for normal displacement, and 3.06 mm versus 2.53 mm for tangential position. This is expected, considering the high sensitivity of glabrous skin [Sobinov and Bensmaia 2021], which is located primarily on the anterior and medial regions of the upper arm. The difference in JND around the upper arm can be used in future to inform module placement and specific feedback mapping that takes this into account when rendering sensory cues. PSE results, shown in Fig. 4.5(right), reveal that user ability to interpret tangential position is accurate to within $\pm 20\%$ when multiple modules are active. Unfortunately, module 4 suffered electronic failure during evaluation, so results for it were only obtainable for two users. PSE for remaining modules followed a similar pattern to previous results; the anterior region of the forearm was found to be more sensitive to stimuli, which may account for user over-estimation of tangential position in modules located in these regions, while the reverse was true for modules located toward the less sensitive posterior regions. It is hypothesised that PSE results could be improved by increasing the travel of the linear drive, and improving the geometry of the servo arm to contact more skin.

4.5 Evaluation

Together, the continuous controller and the haptic armband allowed closed-loop continuous control to be realised, illustrated in Fig. 4.1. The closed-loop continuous controller was evaluated via a control group study with four conditions: closed-loop continuous control (CLCC group), open-loop continuous control (OLCC group), closed-loop discrete control (CLDC group), and open-loop discrete

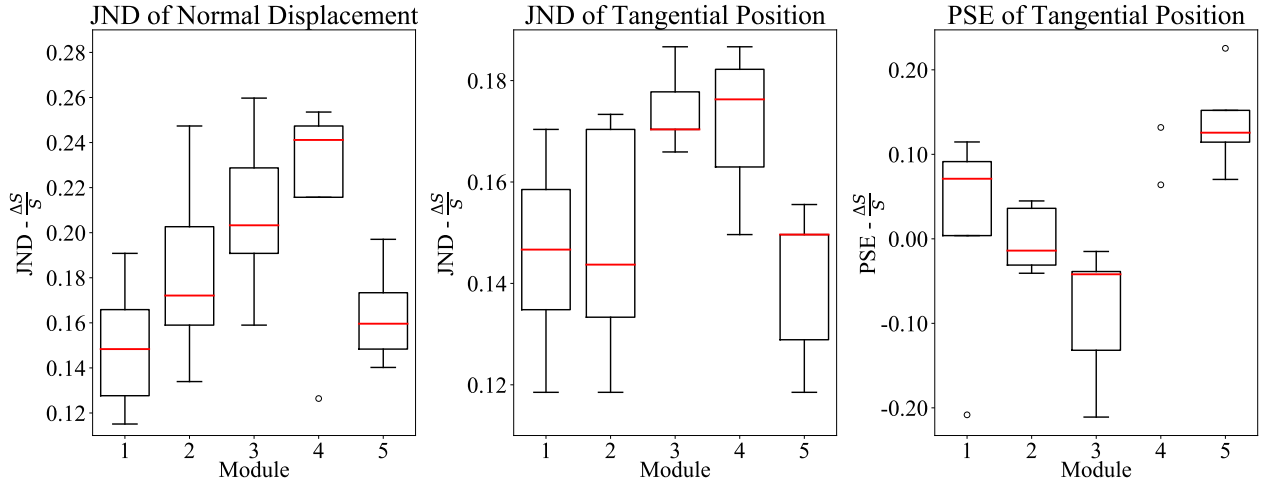


Figure 4.5: Psychometric properties of normal displacement and tangential position feedback rendered to the upper arm of users. Left: Just noticeable difference (JND) of normal displacement for each module, measured with a nominal displacement of 3.0 mm. Middle: JND of tangential position for each module, measured with a nominal position of 17.5 mm. Right: PSE of tangential position for five modules used simultaneously (note that module 4 suffered an electrical fault and only 2 user results are presented).

control (OLDC group). Groups of 7 participants without upper limb difference performed isolated control tasks (position and force matching tasks), isolated sensory tasks (object detection tasks), and contextual activities of daily living to evaluate the physical performance of the controller. To evaluate the psychological effects of the controller, task load and psychological embodiment were quantified respectively using the NASA Task Load Index questionnaire [Hart and Staveland 1988] and an adapted version of the Prosthesis Embodiment Scale for Lower Limb Amputees [Bekrater-Bodmann 2020] and the Avatar Embodiment Questionnaire [Peck and Gonzalez-Franco 2021] (which are in turn based on the rubber hand illusion [Botvinick and Cohen 1998]) with two added questions to gain an understanding of the role of proprioceptive feedback in embodiment (the questionnaire is shown in Appendix A, Table A.3). The controller was evaluated by participants across three sessions: position matching (stage 1), force matching and object detection (stage 2), and clinical dexterity assessments (stage 3). The embodiment questionnaire was administered prior to starting (stage 0), then after each subsequent stage. During stages 1 and 2, the prosthesis was desk-mounted, and during stage 3 participants donned the prosthesis (see Fig. 4.6). The NASA-TLX questionnaire was administered after each stage. 10 participants with upper limb difference completed the experiments as a series of case studies (the characteristics of whom are shown in Table 4.1), evaluating how the presented technology can translate to end-users. A post-study interview was conducted with each of the 10 participants with upper limb difference to gain greater insights into specific causes of increased or decreased task load and embodiment. Fig.4.1 outlines the experiments performed to evaluate its physical and psychological performance.

Table 4.1: Summary table of participant characteristics of participants with limb difference and identified factors that influence perception.

Participant	ULD	Cause	Years Since	Own Prosthesis	Frequency of Use	Factor 1	Factor 2
001	RABE*	C (TI)	26 (8)	Cosmetic	Infrequent	Functionality	Aesthetics
002	LABE	PS	5	None	-	Comfort	Functionality
003	LABE	C	30	None	-	Aesthetics	Functionality
004	(RABE) LAAB	TI	9	Body-Powered	Daily	Functionality	Comfort
005	RABE	C	31	Static	Infrequent	Visuomotor	Functionality
006	RABE	C	30	None	-	Visuomotor	Aesthetics
007	LABE	C	28	Static	Frequent	Functionality	Aesthetics
008	RABE [†]	TI (PS)	24 (6)	Static	Infrequent	Visuomotor	Aesthetics
009	LABE	C	22	Static	Frequent	Functionality	Aesthetics
010	LABE*	TI	3	Static	Infrequent	Visuomotor	Functionality

Upper limb difference sides listed: RABE (right arm), LABE (left arm); levels listed: XXBE (below elbow), XXAE (above elbow). For bilateral upper limb differences the side tested is shown in brackets, and details for the tested side are shown. Causes listed: congenital (C), traumatic injury (TI), planned surgery (PS). For participants with secondary causes of upper limb differences, secondary cause is shown in brackets. Factors listed are obtained from the post-study interview. *Participants 001 and 010 had high limb differences, resulting in no functioning elbow joint. [†]Participant 008 had partial paralysis of the right arm. Full participant characteristics are listed in Appendix A Table A.1.

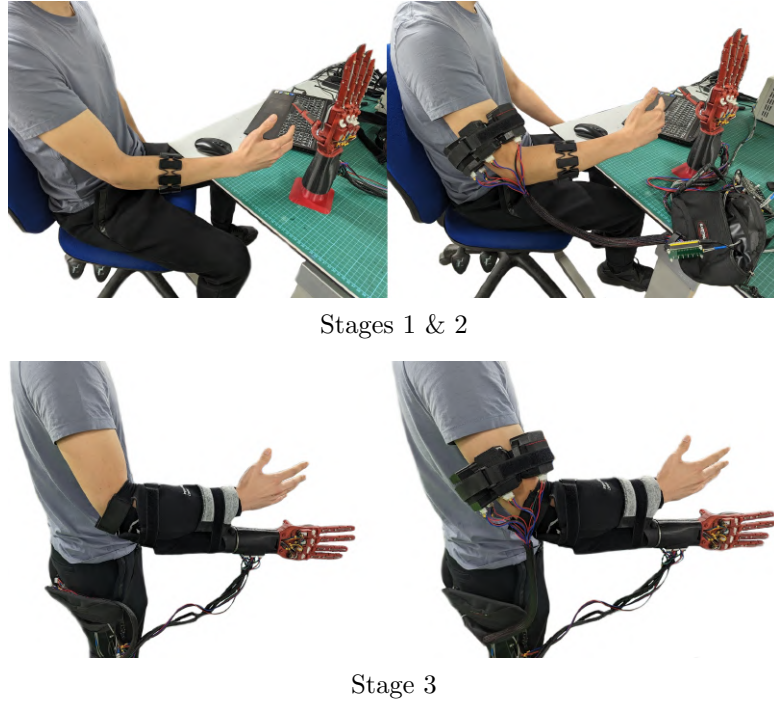


Figure 4.6: Experimental setup for participants without limb difference. Experimental setup for participants without limb difference for stages 1 and 2 (top) and 3 (bottom), in open-loop conditions (left) and closed-loop conditions (right).

4.5.1 Isolated Tasks

The setup of the position matching task is shown in Fig. 4.7. During this task, participants were asked to match target positions of the fingers and wrist of the prosthesis shown in red on a computer display for a series of combinations of controlled DOFs. For each DOF combination, participants were given 10 training trials, during which the actual position of each motor was shown in green, then 10 test trials without the actual position of each motor being shown. DOF combinations increased in complexity from single DOF motions to dual DOF motions during the task.

The setup of the force matching task is shown in Fig. 4.8. During this task, participants were asked to match target prosthesis motor forces, again shown in red on a computer display for each of the grasping DOFs (DOF I and DOF III). Again, participants were given 10 training trials, during which the actual motor force was shown in green, then 10 test trials without the actual motor force being shown.

To test participant ability to classify grasped objects from feedback alone, participants were blindfolded and asked to discriminate between 5 objects during 25 randomised order blindfolded trials, after 2 training grasps of each object. The objects, shown in Fig. 4.9, consisted of a bleach bottle, a plastic strawberry, a soft brick, a screwdriver, and a tuna can.

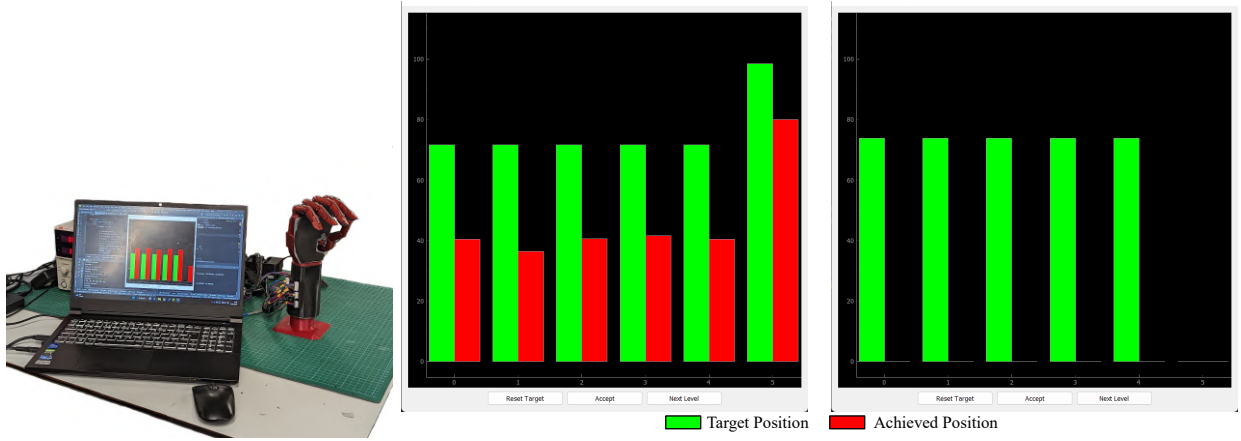


Figure 4.7: Setup of the position matching experiments. Position matching experiments were performed with the prosthesis desk-mounted (left). During training, participants were exposed to explicit visual feedback showing the position of the 5 finger motors and 1 wrist motor of the prosthetic hand in the form of the red bars showing achieved position on the graphical user interface (middle). During testing, the red bars were removed, leaving only the green bars showing target position (right).

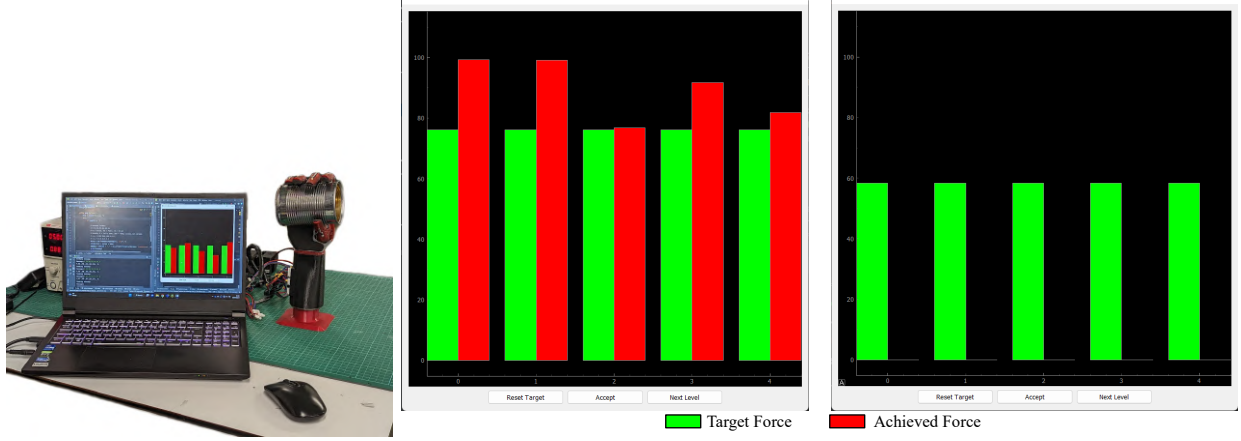


Figure 4.8: Setup of the force matching experiments. Force matching experiments were performed with the prosthesis desk-mounted (left). During training, participants were exposed to explicit visual feedback showing the force applied by the 5 finger motors in the prosthetic hand in the form of the red bars showing achieved force on the graphical user interface (middle). During testing, the red bars were removed, leaving only the green bars showing target force (right).

4.5.2 Contextual Activities of Daily Living

The two dexterity assessments used in this study were the Box and Blocks Test [Trombly and Scott 1983] and the Jebsen-Taylor Hand Function Test [Jebsen et al. 1969], shown in Fig. 4.10. Each participant completed the BBT 5 times, and each task of the JTHFT 1 time.

4.6 Results

4.6.1 Isolated Control Tasks

Position and force matching tasks evaluated the isolated control ability of participants. Participants matched 10 target positions for 5 combinations of controllable DOFs and target forces for the 2 graspable DOFs. Mean absolute error (MAE) results for the OLCC and CLCC groups and participants

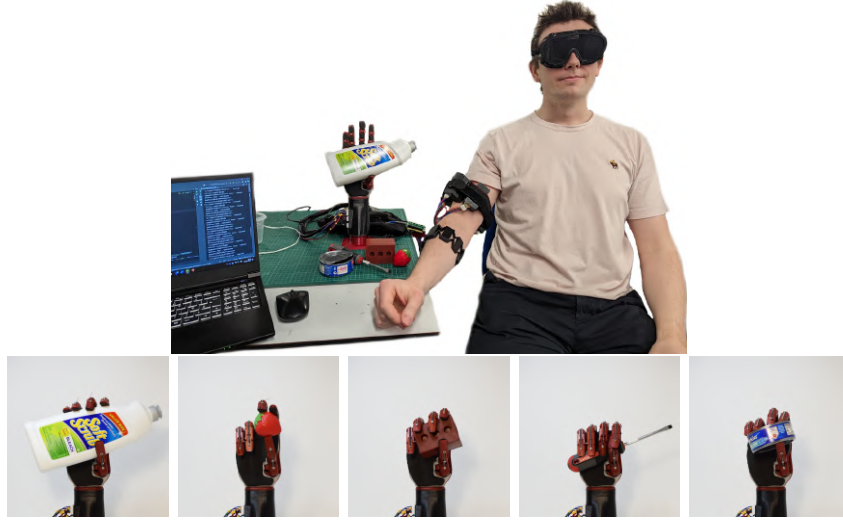


Figure 4.9: Setup of the object identification experiments. During training, participants were able to see the hand grasp each object twice. During testing (top), participants wore a blindfold and each object was grasped five times in a random order. The five objects taken from the YCB object and model set used for object identification experiments (middle row): a bleach bottle, a strawberry, a soft brick, a screwdriver, and a tuna can.

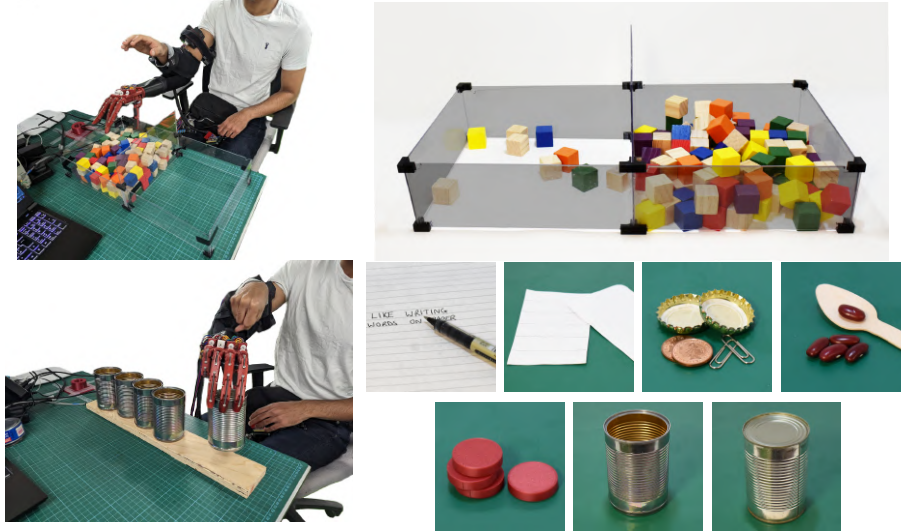


Figure 4.10: Dexterity assessments performed by participants. Top: the Box and Blocks Test: participants must transfer as many blocks as possible from one half of the box to the other in 1 minute. Left: a participant without limb difference completing the Box and Blocks Test. Right: assembled Box and Blocks Test. Bottom: the Jebsen-Taylor Hand Function Test. Left: a participant without limb difference completing the Jebsen-Taylor Hand Function Test. Right: Tasks from the Jebsen-Taylor Hand Function Test, from left to right, top row: (J1) writing, (J2) simulated page turning, (J3) small objects, (J4) simulated feeding. From left to right, bottom row: (J5) stacking checkers, (J6) large, light objects, and (J7) large, heavy objects.

with ULD are shown in Fig. 4.11. For position matching results, statistical significance was calculated between the OLCC and CLCC groups with paired two-sided t -tests, after confirming normality with Shapiro-Wilk tests ($p < 0.05$). During testing, the OLCC group exhibited a significantly higher MAE than the CLCC group in four cases, in both single and dual DOF motions, and produced a MAE that was 36.5% higher on average across all motions. Statistical significance was found using a two-sided

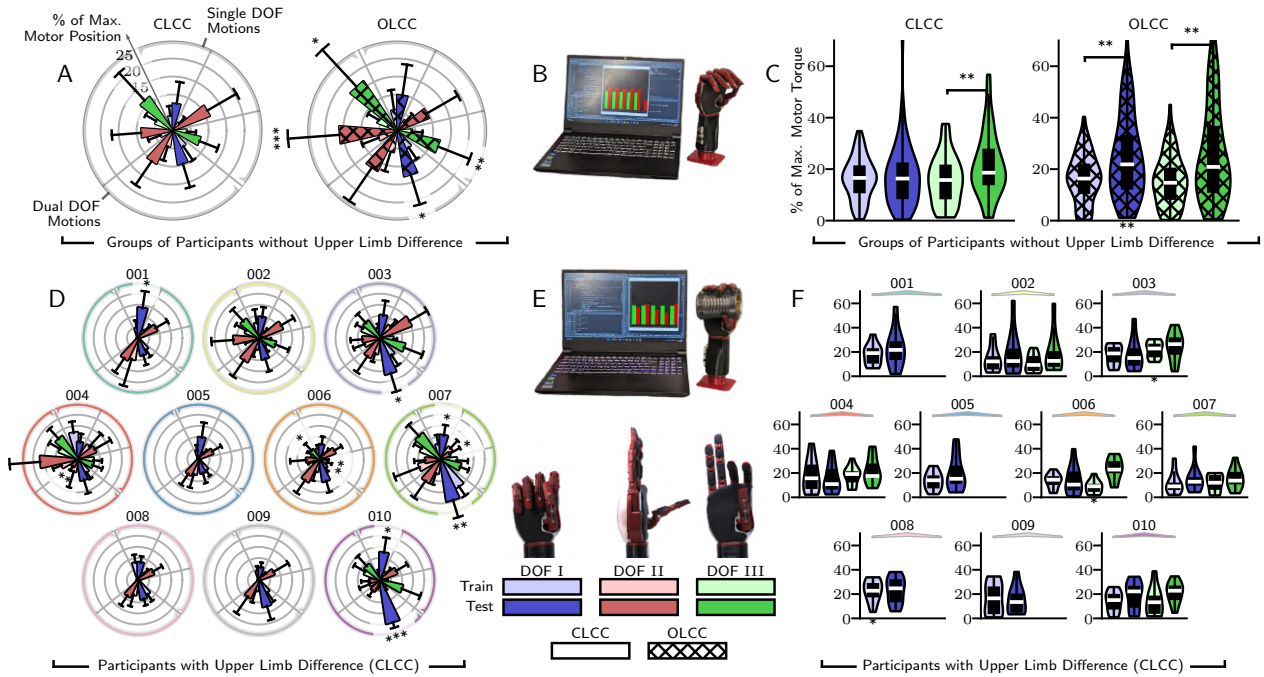


Figure 4.11: Participant results of isolated control tasks. (A, B, D) Mean absolute error of groups of participants without limb difference (A) and participants with limb difference (D) during training and testing trials of a position matching task with the prosthetic hand, with setup shown (B). Participants were asked to match target positions in sets of single and dual degree of freedom motions, performed with no prior training starting from 1 degree of freedom motions, working to 2 degree of freedom motions, corresponding to the clockwise direction on each plot. Results of paired t -tests at $*p < 0.05$, $**p < 0.01$, and $***p < 0.001$ levels between the OLCC participant group and the CLCC participant group during testing are shown. (C, E, F) Mean absolute error of groups of participants without limb difference (C) and participants with limb difference (F) during training and testing trials of the force matching experiment, with setup shown (E). Participants were asked to match target forces along the two grasping degrees of freedom. Results of paired Mann-Whitney U tests at $**p < 0.01$ level between training and test results of OLCC and CLCC groups (C) are shown as linked asterisks on respective plots. In all plots, error bars show one standard deviation, and paired Mann-Whitney U tests at $*p < 0.05$, $**p < 0.01$, and $***p < 0.001$ levels between individual participants with limb difference and the CLCC participant group during testing are shown as floating asterisks on the plots for the OLCC group (A, D) and individual participants with limb difference (C, E), respectively.

Mann-Whitney U test between individual participants with ULD and the OLCC group in 10 cases, however only 6 of these cases—DOF I of participants 001, 007, and 010 during single DOF I motions, and DOF I of participants 003, 007, and 010 during dual DOF I + DOF II motions—represent a significant increase. These coincide with the first actions tested in single and dual DOF motions, and also the highest number of moving joints (5 fingers in DOF I) for the participant to monitor. This is partially explainable by participants learning to activate unused muscles leading to improved results on later motions, however this was not experienced by all.

Force matching results show that the OLCC group exhibited a worse transition from training to testing, with a significant increase in the MAE of both grasping DOFs, than the CLCC group, which only exhibited a significant increase for DOF III. Furthermore, the OLCC group had a significantly higher MAE than the CLCC group for DOF I ($p < 0.01$), found using a Mann-Whitney U test.

On average, MAE of the OLCC group is 31.6% higher than the CLCC group across both DOF during testing. The MAE of DOF III during training for participant 006 was significantly lower than the corresponding DOF for the CLCC group during training. Participants 003 and 008, however, performed significantly worse during training for DOFs III and I, respectively. It should also be noted that, in general, a greater amount of variation was observed for DOF III than DOF I, potentially due to the choice of the tertiary reference muscle contraction. Raw position and force error results of participant groups and individual participants with ULD are shown in Appendix A Figs. A.2-A.4.

4.6.2 Isolated Sensory Tasks

Participants attempted to identify 5 objects while blindfolded; a bleach bottle, a plastic strawberry, a soft brick, a screwdriver, and a tuna can. These were presented 25 times in a randomised order (5 trials per object), after 2 training (non-blindfolded) trials. Results, shown in Fig. 4.12, highlight that continuous control users benefit from sensory feedback, unlike discrete control users. The CLCC group performed comparably to the OLDC group, marginally better than the OLDC group, and significantly better ($p < 0.05$) than the OLCC group, calculated using a Mann-Whitney U test. Participants with ULD generally performed similarly to the CLCC group in terms of average accuracy, with exceptions. Individual confusion matrices (shown in Appendix A Fig. A.6) show that participants 002 and 003 struggled to distinguish between smaller diameter objects. Participants 004 and 008 were unable to identify objects due to sensory impairment from skin graft and nerve damage, respectively, and even though both could perceive general changes in stimulation during isolated control tasks, they could not resolve this at finger-level to identify objects. Participant 006 consistently misidentified the bleach bottle as the soft brick and vice-versa — swapping classifications of these objects yields the faded results shown, which are closer to the expected CLCC group results.

4.6.3 Contextual Activities of Daily Living

The contextual performance of participants was evaluated with assembled versions of two clinical dexterity assessments: the Box and Blocks Test [Trombly and Scott 1983] (BBT) and the Jebsen-Taylor Hand Function Test [Jebsen et al. 1969] (JTHFT). Seen in Fig. 4.13, results of both the BBT and tasks involving static grasp showed no difference between any group. Manual tasks, however, were performed faster by groups using discrete controllers: on average 36.2% and 23.8% faster by the OLDC, and CLDC groups, respectively, than the CLCC group. Page turning was significantly slower ($p < 0.05$) than the OLDC group, calculated using a Mann-Whitney U test. Precision tasks were on average performed fastest by the CLCC group, while the OLCC group showed no improvement over discrete groups. On average, precision tasks were performed 3.5%, 38.1%, and 37.4% slower by the OLDC, CLDC, and OLCC groups, respectively, than the CLCC group. Variance of precision task completion time was also reduced for the CLCC group compared to the OLDC group, indicating a

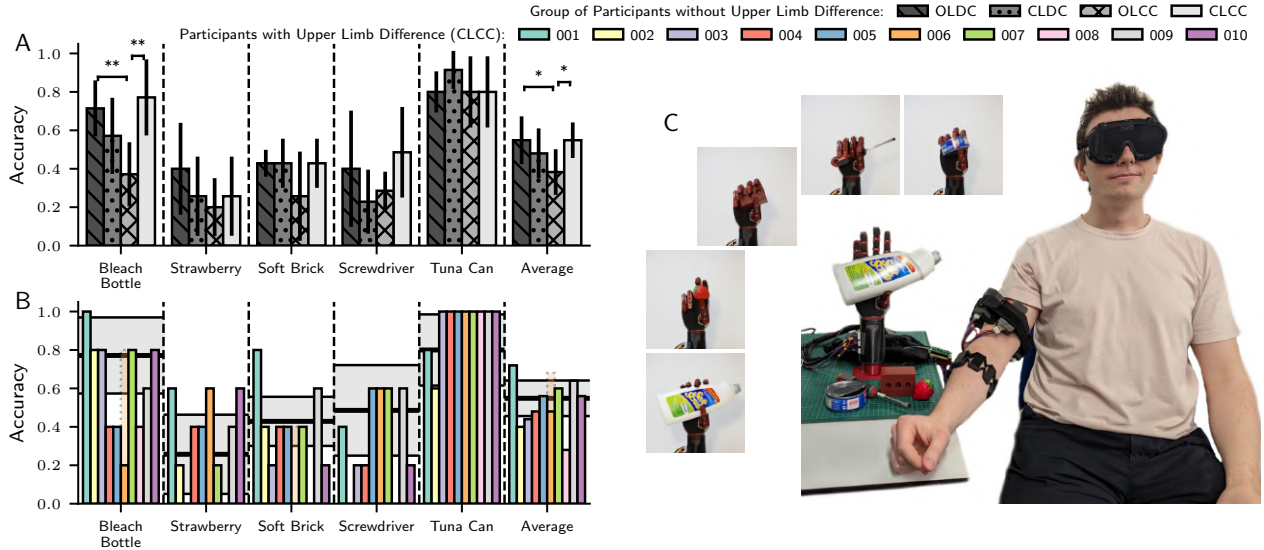


Figure 4.12: Participant results of isolated sensory tasks. **(A)** Object classification accuracy of groups of participants without limb difference. Statistical significance of paired Mann-Whitney U tests shown at $*p < 0.05$ and $**p < 0.01$ levels. **(B)**: Object classification accuracy of individual participants with limb difference, mean and ± 1 standard deviation of the CLCC group results are shown for comparison as a black line and shaded region, respectively. The faded results shown for participant 006 are produced by swapping their predictions for the bleach bottle and soft brick due to consistent misclassification between the two objects. Note: random chance is 0.2. **(C)** Experimental setup; participants grasped five objects five times in a random order without visual feedback. Objects (clockwise): bleach bottle, strawberry, soft brick, screwdriver, and tuna can. Confusion matrices of participant groups and individual participants with limb difference are shown in Appendix A Fig. A.5 and A.6, respectively.

more consistent performance among participants.

Results of participants with ULD generally aligned with CLCC group results, with some notable exceptions. Participant 002 managed to ‘hack’ the simulated page turning task by flicking the paper over with the thumb of the prosthesis extended. Participants 004 and 008 completed the small objects task much more slowly than other participants with ULD and the CLCC group, due to the condition of their ULD preventing compensatory movements from being performed. Participant 002 could not complete the small objects task and participants with ULD 001 and 002 could not complete the large, heavy objects task due to fatigue. The residual limbs of participants 001 and 010 with ULD were both such that neither participant had a functioning elbow joint, which prevented the completion of the small objects task. Participant 008 used an elasticated sling held by their opposing arm due to partial paralysis of the right arm (see Appendix A Fig. A.1h), which restricted wrist rotation and made the large, heavy objects task uncompletable.

4.6.4 User Perception

Participants completed task load and embodiment questionnaires four times during the study: stage 0 - pre-start (about their own prosthesis), stage 1 - after position matching, stage 2 - after force matching and object detection, and stage 3 - after dexterity assessments. Task load was evaluated

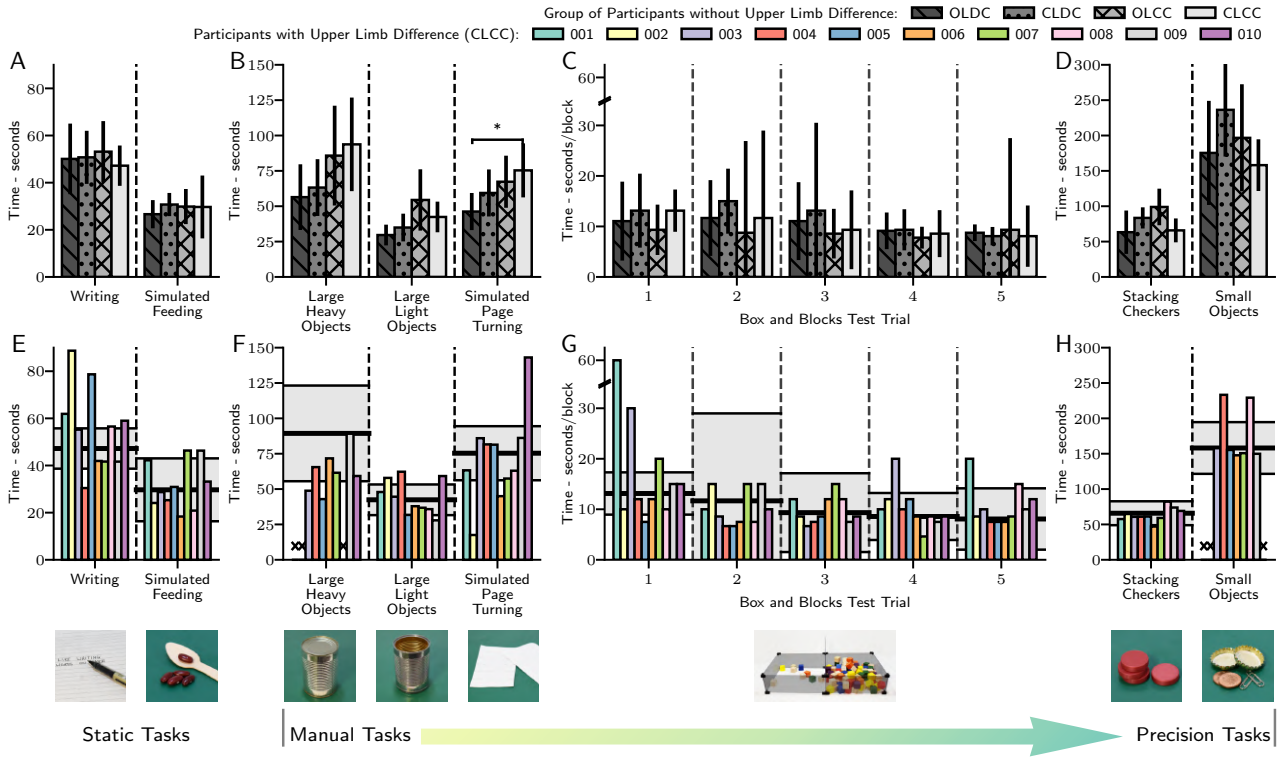


Figure 4.13: Participant results of dexterity assessments. (A - H) Dexterity assessment results of groups of participants without limb difference (A-D) and individual participants with limb difference using the closed-loop continuous controller (E-H) performing tasks from the Jebsen-Taylor Hand Function Test that are static tasks (A, E), manual tasks (B, F), and precision tasks (D, H), and the Box and Blocks Test (C, G). In (E-H), mean and ± 1 standard deviation of the CLCC group results are shown for comparison as a black line and shaded region, respectively. Statistical significance of paired Mann-Whitney U tests shown at $*p < 0.05$ level.

using the NASA Task Load Index (NASA-TLX) questionnaire [Hart and Staveland 1988], during which aspects of task load are self-reported on a 20-point scale (displayed in Fig. 4.14 with a maximum value of 100, interval of 5). Fig. 4.14 shows participant responses to the NASA-TLX questionnaire; as seen, completing stage 1 with a continuous controller elicited a higher physical demand than for participants using a discrete controller, with statistical significance calculated using a Mann-Whitney U test between both the OLCC and CLCC groups and the OLDC group ($p < 0.01$), and the CLDC group ($p < 0.05$). This is expected — discrete control users could only produce binary motions and forces, and therefore were not required to use the prosthesis to a point where physical demand became high. After stage 1, this effect was negated for the CLCC group, who had a 20.2%, 22.7%, and 31.2% lower reported physical demand for stage 3 than the OLDC, CLDC, and OLCC groups, respectively. Interestingly, even with the added 0.40 kg of the haptic feedback armband, closed-loop groups showed no associated increase in physical demand, potentially because it was mounted close to the body on the upper arm. Perceived performance was approximately consistent across groups for stages 1 and 3, whereas in stage 2 the CLCC group exhibited a significantly higher perceived performance than the CLDC group ($p < 0.01$) calculated using a Mann-Whitney U test. Compared to the OLDC, CLDC, and

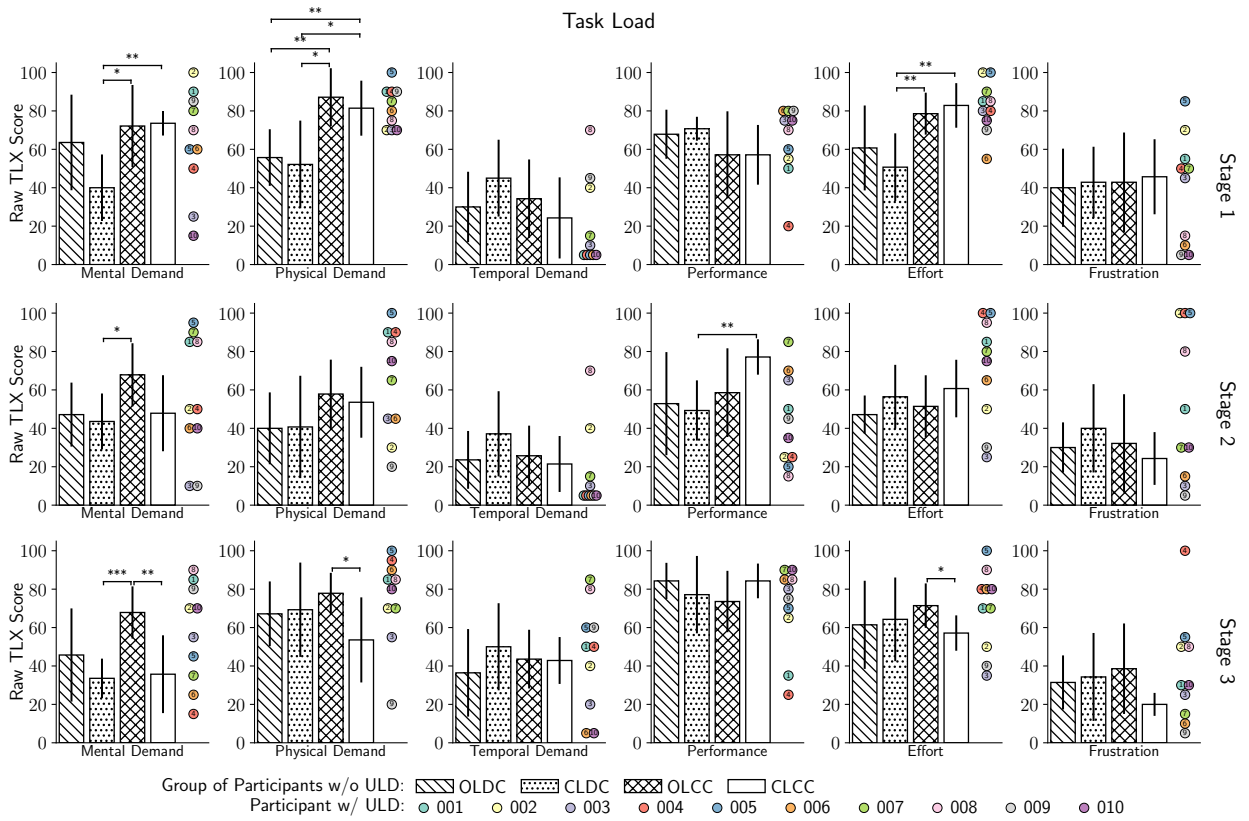


Figure 4.14: Task load responses of participants. Responses of participants to the NASA-TLX questionnaire after stages 1, 2, and 3 of the study.

OLCC groups, this corresponded to a 45.9%, 56.5%, and 31.7% relative increase in respective perceived performance by the CLCC group. Perceived frustration of participant groups showed no statistical significance between groups, however, by stage 3, CLCC group frustration is 36.4%, 41.7%, and 48.1% lower than the OLDC, CLDC, and OLCC groups, respectively. While participant groups exhibited relatively low variance, participants with ULD were extremely heterogeneous. Physical demand for participants with ULD was higher than those without across all stages. The majority of participants with ULD were not prosthesis users, and those that were used body-powered or static prostheses. Activating muscles that are rarely used and a larger weight on the residual limb heightened the physical toll of myoelectric prosthesis use. For many participants, frustration was linked to perceived performance. This is most visible for participants 002, 004, 005, and 008 at stage 2.

Fig. 4.15 also shows the responses of participant groups and individual participants with ULD to statements from the embodiment questionnaire. A post-study interview was conducted with each participant with ULD to further understand perception responses. Two primary perception-influencing factors for each participant with ULD were identified from interviews, and are shown along with a summary of participant characteristics in Table 4.1.

Ownership (statement 1) increased for most participants, with the sharpest rise coinciding with donning the prosthesis in stage 3. In contrast, participant 002 reported a sharp drop in ownership stage 3, even though perceived performance, volition, and vividness were all relatively positive. Here,

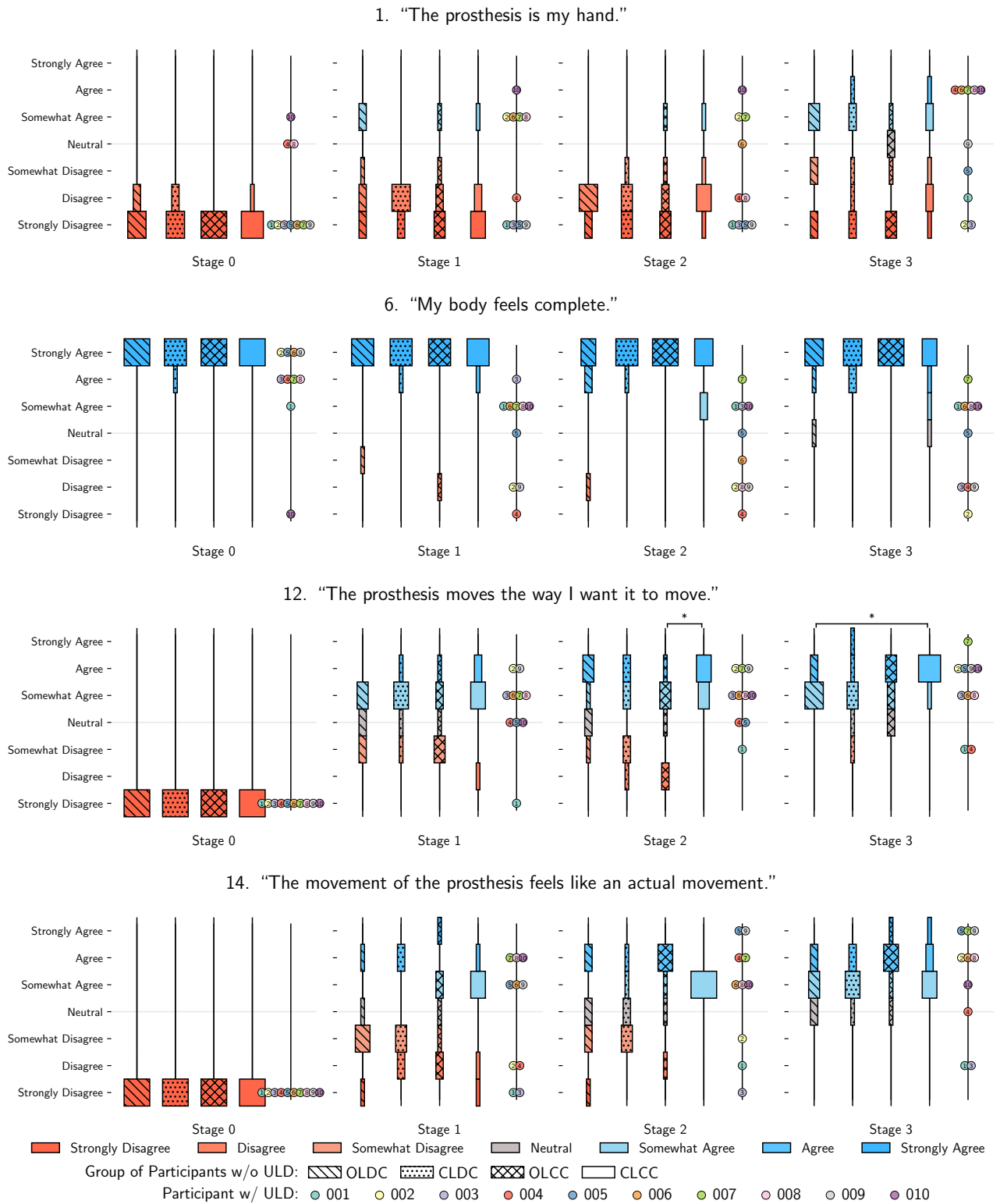


Figure 4.15: Prosthetic embodiment responses of participants before (stage 0) and during (stages 1-3) the study. Responses of participants to the prosthetic embodiment questionnaire statements 1. 'The prosthesis is my hand', 6. 'My body feels complete', 12. 'The prosthesis moves the way I want it to move', and 14. 'The movement of the prosthesis feels like an actual movement'. Responses to all questions are shown in Appendix A Fig. A.7.

a high value was placed on a lightweight prosthesis and secure socket, which could not be achieved with the research socket. During the desk-mounted stages 1 and 2, embodiment was partially aspirational: "...when it's on the table, you can see it's a hand and you can relate to that as being your hand

[...] with the hope that it will work and you will gel with it”. Participant 008 exhibited a decreased ownership after stage 2; visuomotor connection with the prosthesis was important in incorporating the prosthesis into their body, made even more important by nerve damage heavily impairing acute sensory feedback from the haptic armband. During stage 3 this visuomotor connection was restored, and ownership increased again.

Participants without ULD consistently responded positively to body completeness (statement 6), in contrast to participants with ULD, whose responses actually became more negative over the course of the study. This was prominent for participant 002, a non-user in their daily life, who dropped from ‘Strongly Agree’ to ‘Strongly Disagree’ from stages 0 to 3, stating that when “dealing with prostheses it comes very quickly back to you that you have lost an appendage”. Completeness fluctuated for participants 006 and 008: both experienced a drop at stage 2 which was restored at stage 3, aligning with the removal of the visual connection with the prosthesis during stage 2. Participants 007 and 010 experienced a positive trend in completeness. Participant 007, who had a congenital ULD, responded ‘Agree’ at stage 0, which dropped slightly to ‘Somewhat Agree’ after stage 1, then increased to ‘Agree’ after stage 2, where it remained. Participant 010, a relatively recent patient of amputation, responded ‘Strongly Disagree’ at stage 0, which increased to ‘Somewhat Agree’ after stage 1, where it remained. Both participants cited functionality as a key factor, with participant 007 stating “I was less reliant on my right hand, and actually having another option led to me feeling more complete”.

Volition (statement 12) and vividness (statement 14) became increasingly positive, with the CLCC group exhibiting the sharpest rise during earlier stages. The CLCC group perceived significantly higher volition after stage 2 than the OLCC group ($p < 0.05$), calculated using a Mann-Whitney U test. Participants with ULD responded similarly: an increase in volition for participant 001 corresponded with an improved understanding of the combined control and sensory feedback, a sentiment shared by participants 007 and 008. Similarly, participant 005 perceived control becoming more natural as tasks became more contextual, “By the end it wasn’t ‘contract this muscle’, it was ‘pick that up’. Then I was doing it as a natural reaction”. Aspirational use was important to participant 007, and simultaneously actuating DOFs aided this, “grabbing something and turning, I could see how that would be useful”. Participant 003 responded similarly, however was limited by the study environment, “The exercises felt like not ‘real’ experiences in that we were [...] in a research lab. They’re not tasks that I’d be doing in my day-to-day life... What would make me feel like it was my hand would be to use it in real life scenarios”. Continuous control was beneficial for participant 008, “thinking of that action was sort of transported [...] into the hand in a smoother movement, whereas if it was jerky, I would never have been able to [perform precision tasks]”.

Further results, shown in Appendix A, Fig. A.7, show that sensory feedback, predictably, improved perceived position, force, and touch.

4.7 Discussion

4.7.1 Closed-Loop Continuous Control Promotes Natural Motion and Improves Participant Performance

Results demonstrate that the CLCC group outperform other groups in isolated control, sensory, and precision dexterity tasks, and that individual participants with ULD generally demonstrate performance levels comparable to those without ULD. Exceptions to this were generally linked to the physical condition of each participant’s upper arm or residual limb.

Group responses to the task load questionnaires highlight further benefits of closed-loop continuous control, with participants experiencing a lower physical demand and frustration than other groups in comparable settings. However, there are key differences between participants with and without ULD; the former generally found each stage more physically demanding, corresponding to residual limb muscle weakness unless the participant is a myoelectric hand user, and weight distributed across a shorter residual limb. Perceived performance and frustration were also reported more negatively by participants with ULD, and were linked; fostering perceived performance during rehabilitation is of critical importance to reduce patient frustration. Embodiment results highlight an earlier increase volition (statement 12), and vividness (statement 14) in participants from continuous control groups than in discrete control groups. Responses of participants with ULD fell within expected ranges for the CLCC group for each of these questions, showing that these benefits can translate to real users with ULD.

Although results are positive, the introduced controller falls short of participant desires in some areas. The most common requests were reduced delay and improved accuracy. Delay occurs because the controller is reactive, rather than predictive, and because of latency in the prosthesis. Accuracy issues, across all groups, occurred when carrying out tasks while wearing the prosthesis. The added weight on the residual limb is the main cause of this, and can be mitigated by recalibration and user practice to isolate muscle groups.

4.7.2 Open-Loop Discrete Control Provides Key Benefits

The effectiveness of standard open-loop discrete control in many scenarios is difficult to ignore. This was most prominent in object identification, where the OLDC group were on par with the CLDC group, based on auditory feedback alone. Audition as a source of ‘incidental’ feedback, where the sound of each finger motor can be used to identify motor position and grasping force, among other things [Sensinger and Dosen 2020], is a well-known skill obtained by prosthetic hand users. This ability is reduced when using a continuous controller because motor speed is no longer consistent, resulting in poor identification performance of the OLCC group. Feedback did not improve object identification performance of discrete control users. During grasping, the dominant feedback mechanism was normal

displacement, rendering finger torque. Because the hand is closed discretely with maximum force, there is little differentiating the feedback from each finger to a participant. Instead, the transient feedback of sequential increases in finger torque as each finger contacts an object must be observed. It is possible that tactile sensors on the prosthesis would improve object identification and overcome proprioceptive feedback limitations, as well as promoting embodiment.

Discrete control groups also completed manual dexterity tasks faster than continuous groups, possibly because discrete control only requires muscle activity to reach a desired pattern to fully close the hand. This is somewhat faster and easier to sustain than maintaining a fully closed hand with continuous control. This effect was most visible on the large, heavy objects task, during which DOF I and II must be fully activated together. The benefits of discrete control can be leveraged in future continuous controllers. Methods such as mode-switching, popular in extending the functionality of conventional controllers, between discrete and continuous control could allow users to benefit from a full range of manual and precise dexterity.

4.7.3 End User Heterogeneity Leads to Complex Perception Results

It is easy for researchers to assume that participants who acquired an ULD later in life may feel ‘less complete’ or more ‘in need’ of a prosthesis than someone with a congenital ULD. It was found that this is not necessarily the case. All participants with ULD in this study, except for participant 010, viewed their body completeness positively at stage 0, with no clear separation between participants with congenital ULD versus acquired ULD. Participant 004 — who had an acquired ULD — went so far as to say, “I’ve had two bodies. I had one with arms and legs and now I’ve got a body with no legs, bit of an arm missing, a lot of the other arm missing. ‘Body complete’ to me is just wearing that one [body-powered] prosthesis on my right arm.”. By contrast, participant 010, who relatively recently had undergone amputation, stated “I know my body is not complete because I can look at [my arm], it’s gone”. During the study, varied results in terms of body incorporation and completeness were observed, confirming high variation reported in literature [Engdahl et al. 2020], however the cause of a participant’s ULD was only a determining factor of perception when it was tied to their performance in a task.

Ideally, enough participants with ULD would be recruited such that analysis is adequately-powered to observe statistical differences between intervention conditions and a control group. In reality, this is improbable due to a small population size, difficulty of recruitment, and significant participant heterogeneity. As a result, studies often rely on a small number of participants with ULD and supplement these with a larger sample of participants without ULD [Furui et al. 2019; Cho et al. 2022], including this study and those documented in chapters 3 and 5. While such studies often show similar physical performance results between participants with ULD and their counterparts without ULD, regardless of demographic differences, new technology often fails to make the leap from research to

wider adoption. This, coupled with unchanging rates of rejection [Biddiss and Chau 2007b; Salminger et al. 2020], make it clear that there is something missing in terms of researchers’ understanding of prosthetic hand use from an end-user perspective. Individual participants with ULD with similar physical circumstances and task results can respond very differently, psychologically, to prosthetic hand use. When a small number of participants with ULD are recruited, effort should be made obtain a more holistic, complete understanding of each participant’s experience.

User expectations and priorities play a vital role in the developing relationship with their prosthesis. As summarised in Table 4.1, the aesthetic qualities of the prosthesis were often an important—but secondary—factor. The anthropomorphic structure of the hand was praised, and played a role in promoting natural motion, ownership, and completeness. However, the length of the prosthesis in relation to their expectation of where their hand should be received mixed responses, with participant 003 stating that the socket extending above the elbow made the prosthesis appear longer than it physically was. Comfort was often a secondary factor in perception, potentially due to the prosthesis only being donned for stage 3, and also that participants were confident that a commercialised iteration of the device would be more comfortable. For others, comfort took on a central role; without a secure socket and lightweight hand, embodiment was more difficult to obtain. Functionality as a priority was often linked with prior non-anthropomorphic prosthesis use. For such participants, body incorporation remained low, even though ownership increased. For example, participants 004 and 009 finished the study with positive and neutral responses to “the prosthesis is my hand”, but negative and strongly negative responses to “the prosthesis is part of my body”, respectively. Corroborating this, participant 001 stated, “[my left] hand is a part of me, whereas I forever see anything [on my right] as something that is just an extension; artificial. So I assign value to being a part of me is how useful that tool is at the end”. The visuomotor connection with a prosthesis can also be critical; the perception that a desired motor signal is related to the visible motion of the prosthesis is intricate, with many contributing aspects such as latency and the correspondence between residual muscle- and prosthesis-actuation. For participants where this was important, the controller’s continuous motion promoted a perception of natural motion, in turn promoting embodiment. Familiarity plays a large role in embodiment [Imaizumi et al. 2016], however, due to the short-term nature of this study, it was difficult for participants to build upon this. This is a drawback of this study, however, even within the time-frame, participants commented on a positive relationship between duration of use and embodiment, with participant 007 stating, “...as my familiarity with the prosthesis grew, it did make me feel like I was looking at more of a hand than a prosthesis”.

Importantly, most participants with ULD in this study had previously rejected myoelectric prostheses. Identifying points when task load increased or embodiment decreased can provide clues to the reasons behind rejection. For example, understanding that participant 002’s sharp drop in embodiment after donning the prosthesis was related to comfort would enable training to be adjusted

to mitigate this. Moreover, rejection is a worst-case outcome; acceptance of the prosthesis by its user is the ideal scenario. Acceptance is difficult to monitor, and a holistic approach is needed over conventional outcome measures.

4.7.4 Benefits of Continuous Control and Closing the Sensory Feedback Loop are Maximised Together

Continuous control and sensory feedback have their individual benefits: continuous control is useful for modulating grasp force and finger position at a fine level and achieving a natural sense of motion. Meanwhile, sensory feedback provides participants with an alternative to auditory feedback and restores a sense of touch to the user. In the experiments performed in this work, each participant group excelled and under-performed at different tasks. The OLDC group were proficient at object identification tasks and manual dexterity tasks, but were, by nature, unable to perform any position or force matching tasks. The CLDC group performed similarly to the OLDC group, except with a slightly reduced acuity for object identification, yet a strong perceived sense of touch. The OLCC group performed position and force matching tasks to a reasonable level, but showed poor object identification results and consistently higher perceived physical demand. Finally, the CLCC group showed improved perception results and performed strongly in every task, leaving only manual tasks to be desired. The results presented in this work show that, to maximise the benefits of continuous control and sensory feedback, both must be realised together.

4.7.5 Comparison with Body-Powered Prostheses

Comparison between the results of the JTHFT with those of the previous chapter (see Fig. 3.15) reveal general improvements in participant performance on each task. In this study, the discrete controller used by the OLDC and CLDC groups used only 4 references — in order to match the 3 degrees of freedom of the continuous controller. This simplified control could explain faster completion times. However, all groups still fall short of the body-powered performance by some way. This may be because a body-powered prosthesis is specifically designed to be a gripper, while an anthropomorphic prosthesis such as the OLYMPIC hand is designed to replicate the form of a human hand.

4.8 Conclusions

In this chapter, a closed-loop continuous myoelectric controller has been introduced, that is able to continuously modulate 3 degrees of freedom of a prosthetic hand from minimal user data, while providing proprioceptive sensory feedback to the user. The controller was created by extending the distance-based controller presented in 3 to produce continuous motion, and by developing a haptic feedback armband that is capable of rendering proprioceptive information from the prosthesis to the

user. The haptic armband is able to render 15 sensory percepts to the user, used in this work to render finger position, finger torque, and wrist position.

The closed-loop continuous controller was evaluated via a control group study, and demonstrated significant benefits in terms of performance in isolated control and sensory tasks, and precision tasks of daily living, over open-loop continuous control. The controller also showed improvements in task load and embodiment over other controllers, and end-users responded positively to the continuous, natural motion. Key benefits of open-loop discrete control were identified as manual task performance and isolated sensory task performance, due to the repeatable, binary nature of the control.

Perhaps most importantly, it was found that task performance often had only a small bearing on embodiment and psychological ownership in end users. Participants with upper limb difference displayed considerable heterogeneity in embodiment questionnaire responses despite exhibiting relatively consistent task performance — even when age, sex, and upper limb difference level and cause were similar. These findings reinforce the generally accepted notion that prosthesis rejection and acceptance is a complex issue that is largely individual in nature. Post-study interviews helped to identify key factors that influenced embodiment and task load, highlighting the importance of an open channel of communication with end-users during the rehabilitation and training process.

The study presented in this chapter has highlighted key benefits of closed-loop continuous myoelectric control, such as more precise motion, and improved embodiment. However, task performance results are still far behind a body-powered gripper. The next chapter will investigate the impact that the design of the terminal device can have on task performance, task load, and how a user’s body responds to the prosthesis.

Chapter 5

The Controlled Prosthesis

This chapter is based on the work presented in:

Digby Chappell, Barry Mulvey, Shehara Perera, Fernando Bello, Petar Kormushev, and Nicolas Rojas (2024a). “Beyond Humanoid Prosthetic Hands: Modular Terminal Devices That Improve User Performance”. In: *IEEE Transactions on Medical Robotics and Bionics (Under Review)*

Digby Chappell, Fernando Bello, Petar Kormushev, and Nicolas Rojas (Sept. 2023). “The Hydra Hand: A Mode-Switching Underactuated Gripper with Precision and Power Grasping Modes”. In: *IEEE Robotics and Automation Letters* 8.11, pp. 7599–7606

Despite the progress made in the previous chapters of this thesis, the results presented for user task performance have still been far from satisfactory. Simple tasks such as stacking four checkers can take anywhere between 50 and 100 seconds, even with the simplest control possible. This raises questions regarding the effectiveness of the prosthetic hand itself. This chapter explores the design of the end effector of the prosthetic hand, identifying benefits in functionality, comfort, and ease of use that can be obtained through improved prosthesis design.

5.1 Introduction

Myoelectric prosthetic hand design has been the subject of decades of research, starting in the 1950s and 60s with simple, single degree of freedom devices [Battye et al. 1955; Sherman 1964; Michael and Crawford 1963]. In the years since, advances in hardware have allowed multiple degrees of freedom to be actuated independently [Kyberd and Chappell 1994; Weiner et al. 2018; Liow et al. 2020; Cho et al. 2022; De Arco et al. 2022], promising to dramatically increase the functionality of such prostheses. However, this has not been the case: user dissatisfaction and rejection rates are high [Kyberd et al. 2007; Pylatiuk et al. 2007; Østlie et al. 2012; Salminger et al. 2020], with a lack of functionality and dexterity often cited as a key reason for this [Atkins et al. 1996; Biddiss et al. 2009; Espinosa and

Nathan-Roberts 2019]. Poor functionality means that adults with upper limb difference are often forced to either change profession or adapt their duties in order to continue working [Datta et al. 2004; Sluis et al. 2009; Postema et al. 2016]. Furthermore, adults with ULD are significantly more likely to experience chronic musculoskeletal pain due to overuse of any intact limb and compensatory motion performed to mitigate shortfalls in prosthesis functionality [Jones and Davidson 1999; Ephraim et al. 2005; Hanley et al. 2009; Østlie et al. 2011c], with modern prostheses showing little evidence of reducing this [Johansen et al. 2015]. It is clear that there is a shortfall between current developments and users' needs.

This shortfall, in part, is due to the design philosophy behind the majority of myoelectric hands: anthropomorphism. Anthropomorphic hands seek to imitate the form and function of human hands. The grasping versatility of a human hand is unparalleled by any other natural or mechanical gripper. Human hands are the result of a complex system of motor and sensory pathways that enable humans to perform extremely dexterous motions, switch at ease between precision and power grasps, and comply and adapt to grasped objects of varying shapes, sizes, and weights [Sobinov and Bensmaia 2021]. To achieve this in a prosthetic hand is extremely challenging, given the limitations associated with housing such complex mechanical, control, and sensing technology within the form-factor of a human hand. Despite the previously mentioned advances in hardware, the number of actuators that can fit in the profile of a hand is limited, meaning that anthropomorphic prostheses—typically actuating between 5 and 7 DOFs—fall far short of the more than 20 DOFs of a human hand. In the majority of multi-articulating prostheses, multiple actuators are allocated to finger flexion [Kyberd and Chappell 1994; Weiner et al. 2018; Liow et al. 2020; Cho et al. 2022; De Arco et al. 2022]. While this does expand the range of actions available to users by controlling which fingers are flexed and extended, this redundancy in flexion actuation does little to increase functionality. Furthermore, modern myoelectric controllers, including the closed-loop continuous controller presented in Chapter 4, are restricted to actuating 1 – 3 DOFs independently and simultaneously [Hahne et al. 2018; Dyson et al. 2018; Dyson et al. 2020], meaning that multiple fingers are flexed at once during operation, and in practice means the five-fingered prosthesis behaves as a two-fingered gripper, in which multiple fingers act as a single wider, compliant finger. Multiple hand designs have shown that it is possible to achieve similar compliance with only a single actuator [Wattanasiri et al. 2018; Laffranchi et al. 2020; Gu et al. 2021], so a potentially fruitful research direction could be to retarget these redundant flexion actuators to increase functionality. In short, looking to an alternative design ideology than the accepted design ideology of anthropomorphism could lead to functional benefits for prosthetic hand users.

When looking beyond functionality, the psychological role of anthropomorphism cannot be ignored. Although the aesthetic qualities of a prosthesis are typically a factor of secondary importance for users [Atkins et al. 1996; Biddiss et al. 2009; Salminger et al. 2020], it has been observed that

anthropomorphism contributes positively to social acceptance [Arabian et al. 2016; Biddiss et al. 2009] and psychological embodiment (seen in Chapter 4). Developing entirely non-anthropomorphic prostheses risks unnecessary societal pressure for users and may prevent body incorporation, limiting the depth of their psychological acceptance of the prosthesis. A promising direction may therefore be to enable users to obtain the functional benefits of non-humanoid terminal devices while retaining the option of an anthropomorphic prosthesis when desired. Such an approach allows users to leverage functionality when necessary — such as in the workplace — and aesthetic qualities where social acceptance and discretion are preferred.

In this chapter, an alternative design ideology is investigated: non-anthropomorphism. A taxonomy of the design of upper limb prostheses, shown in Fig. 5.1 a, is introduced, which exposes key areas of unexplored design space that could provide considerable functional benefits to users. Then, four functional prosthetic devices, shown in Fig. 5.1 b-e, are developed and evaluated that illustrate the four high level branches of the taxonomy, each demonstrating large improvements over a conventional myoelectric hand in terms of task performance, comfort, and ease of use. Finally, the mechanical design and evaluation of a grasp-focused, hybrid-actuation prosthetic hand, the Hydra prosthesis is presented (shown in Fig. 5.1 f). This chapter challenges established norms in myoelectric prosthetic hand design, opening the door for further development in a wider, more innovative prosthetic hand design space.

5.2 Related Work

When a limit is placed on the number of controllable degrees of freedom in a prosthetic hand, functional designs are often favoured over aesthetics. The extreme case of this occurs in passive and body-powered prostheses, where the user is able to operate 0 and 1 DOFs, respectively. More than a century ago, non-humanoid body-powered and passive prostheses were developed to achieve tasks that are impossible with conventional anthropomorphic designs [Kyberd 2021]. Today, task specific terminal devices are commonplace for passive prostheses [Hammond et al. 2012; Maat et al. 2018], with commercial options such as the Nicole ALX (Koalaa Ltd; UK) and the TRS Helix (Therapeutic Recreation Systems Inc, Fillauer; USA) widely available. Body-powered prostheses are less varied; the split-hook design is common for general use as a gripper [Smit and Plettenburg 2010; Smit et al. 2012], and far fewer task-specific body-powered prostheses are available, with one notable example being the Ski-2 Terminal Device (Therapeutic Recreation Systems Inc, Fillauer; USA), which allows the user to adjust the angle of a ski pole using a body-powered cable.

Task-specific passive and body-powered prostheses provide make a compelling case for the design of non-anthropomorphic upper limb prosthetic devices, but are functionally capped by their limited degrees of freedom and modes of actuation. In the field of robotics, grippers have been designed

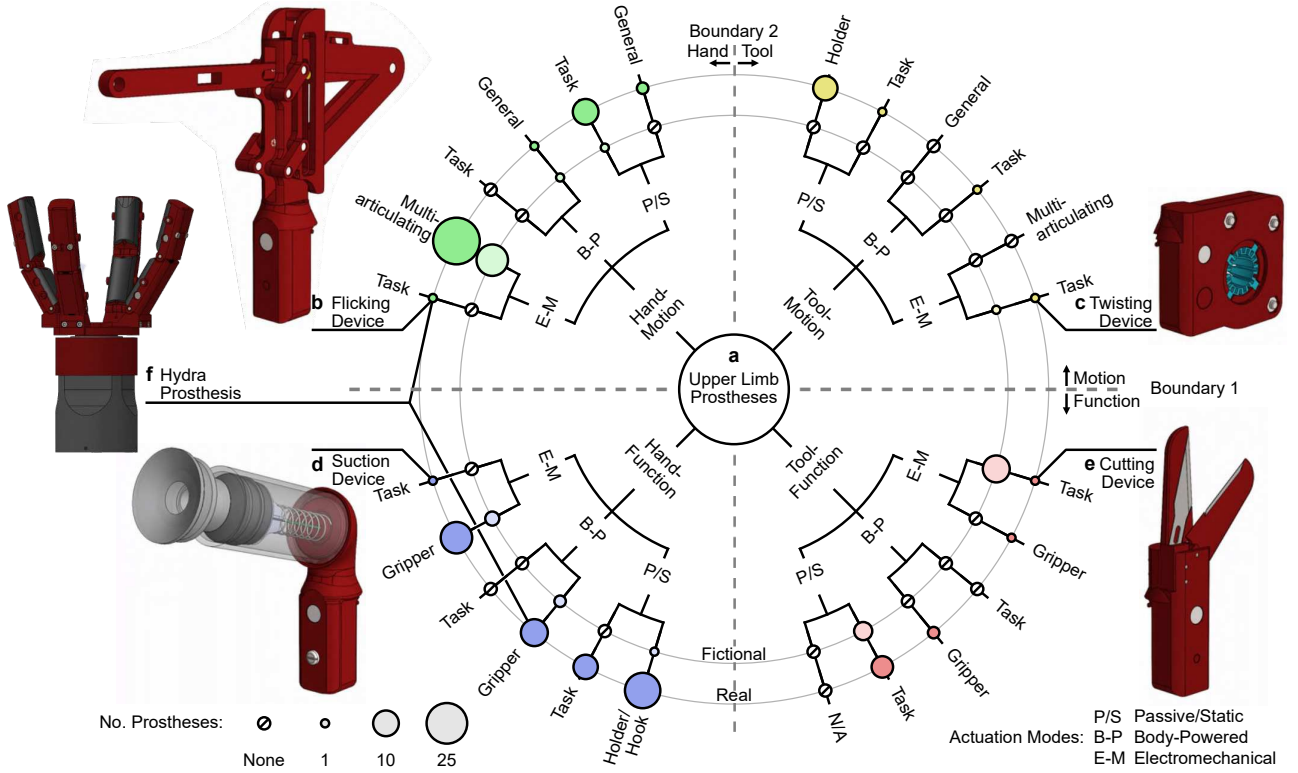


Figure 5.1: A taxonomy of real and fictional upper limb prostheses. **a** A taxonomy of real (seen in clinical use, history, or research) and fictional (seen in works of art and fiction) upper limb prostheses, formed by two high-level boundaries, modes of actuation, and targeted action. Targeted actions are categorised into task-specific or either the dominant form of motion (multi-articulating for electro-mechanical, general for body-powered, and holder for passive/static prostheses) or function (gripper for electro-mechanical and body-powered, and holder for passive/static prostheses). Circle area is proportional to number of instances found. **b-e** Four terminal devices are presented in this work, each in a different branch of the taxonomy, and are the only current examples of real-world task-specific electromechanical prostheses: Hand-Motion, Flicking Device (**b**), Tool-Motion, Twisting Device (**c**), Hand-Function, Suction Device (**d**), and Tool-Function, Cutting Device (**e**). **f** The Hydra Prosthesis, which combines body-powered grasping with electromechanical wrist rotation.

with a reduced number of DOFs to perform targeted functions and manipulations. These grippers are often designed for in-hand manipulation, with specialised DOFs for reorienting and translating grasped objects. Common design features include variable friction surfaces [Spiers et al. 2018; Lu et al. 2020] and the ability to reconfigure the fingers of the gripper in order to translate or rotate a grasped object [Townsend 2000; Rojas et al. 2016; Lu et al. 2021; Kang et al. 2021]. Alternatively, grippers have been designed with carefully tuned joint trajectories in order to perform multiple types of grasps with minimal numbers of actuators. The Meso gripper uses a single actuator to achieve power and pinch grasps with a two-fingers [Bai et al. 2017], with adaptability achieved via a differential pulley in the palm, while the Velo gripper [Ciocarlie et al. 2014] uses a balancing extension tendon that causes the distal phalanges to form a parallel grasp by default, meaning that an enveloping grasp—a necessity for heavier objects—only occurs when an object is actively blocking the proximal phalanges. A promising direction may therefore be to leverage non-anthropomorphism and techniques seen in task-specific body-powered and passive prostheses and robotic grippers in the design of myoelectric

prostheses.

To date, non-anthropomorphism is far less common in myoelectric prostheses, with very few examples of non-humanoid designs existing in literature [Dollar and Howe 2007; Yoshikawa et al. 2023; Hong et al. 2023]. Furthermore, the few existing designs are grippers [Dollar and Howe 2007; Yoshikawa et al. 2023; Hong et al. 2023], focusing on improving existing grasping functionality. With multiple actuators at the designer’s disposal and 1–3 robust myoelectric control outputs, anthropomorphic hands and non-anthropomorphic grippers occupy only a fraction of the possible design space of prosthetic hands. Without the constraints associated with replicating a human hand, alternative, non-humanoid designs of myoelectric prostheses can be a meaningful step towards addressing user needs that have remained unmet for so long.

5.3 A Taxonomy of Real and Fictional Upper Limb Prostheses

To formalise the design of prosthetic hands, a taxonomy of upper limb prostheses, both real and fictional, is created according to the design principles behind them, shown in Fig. 5.1 a. Four high-level branches are identified by asking two boundary-forming design questions: “is the prosthesis producing (or assisting in the production of) a motion or a function?”, and “is the desired action ordinarily completed with a human hand or a tool?” The taxonomy further subdivides the design space of prosthetic hands by identifying the actuation mode and execution mode of the prosthesis.

5.3.1 Creation of the Taxonomy

Taxonomy Level 1: Motion vs Function and Hand vs Tool

At a high-level, upper limb prostheses are split into four branches by posing two fundamental design questions: “is the terminal device producing a motion or a function?”, and “is the desired action ordinarily completed with a human hand or a tool?”. These two questions form four branches in design space (shown in Fig. 5.1) — Hand-Motion, Tool-Motion, Hand-Function, and Tool-Function — each providing a different lens through which to view the design of an upper limb prosthesis.

The first question posed is whether the prosthesis produces (or assist in the production of) motion or function. Here, we interpret tools as a devices intended to perform a particular function, while hands can either be viewed as a more general purpose manipulator, or a motion generator (for example, when producing gestures). We consider multi-articulating prostheses, such as the KIT prosthetic hand [Weiner et al. 2018] or the MSC hand [Cho et al. 2022] as devices that produce motion, being designed to perform multiple grasps and gestures. Meanwhile, existing non-anthropomorphic grippers and single-grasp anthropomorphic grippers, such as the Hannes hand [Laffranchi et al. 2020] and the SoftHand Pro [Godfrey et al. 2018], produce function, generally being designed to perform only one grasp.

The benefit of designing a prosthesis to produce a function becomes clear when looking beyond grasping, at functions such as cutting, drilling, or writing. Even when considering grasp-related functionality, there are many items that are difficult to grasp—even with a human hand—such as very small or flat objects, that become significantly easier with a designated device to perform this function. Considering motion also brings benefits to prosthesis design by bringing non-grasping actions and manipulations into focus. Examples of these actions may be social actions, such as flicking—an action used extensively in social games the world over—or gesturing. Alternatively, these motions may serve to operate tools themselves, such as a prosthesis that produces the motion required to twist a screwdriver, move a pen tip over a planar surface, or button a shirt.

The second question posed is whether the action that is being completed is performed by a human hand or a tool. As expected, there are some actions that lie patently on one side of the boundary or the other. For example, cutting (as opposed to tearing) can only be performed by a tool, meanwhile performing a ‘thumbs up’ gesture is an action that is, without question, human. There are, however, many actions that can be performed by both human hand and tool alike, such as (loosely) screwing in a bolt or grasping a small object. We argue that this grey area is beneficial to the design of prostheses, as it encourages a more diverse set of viable terminal devices to perform a given action depending on context.

Taxonomy Level 2: Actuation Mode

The next level of the taxonomy categorises prostheses according to their actuation mode. Three modes are considered: passive/static, body-powered, and electromechanical. Note that these modes are selected based on options currently available to adults with upper limb difference [Trent et al. 2019], and electromechanical is used as a blanket term for any prosthesis that is not passive/static or body-powered. This distinction is important when considered fictional prosthetic hands, which are often controlled and actuated by unseen, futuristic methods, such as Ulysses Klaw’s arm from the Marvel comics [Lee and Kirby 1966] which is quite literally formed from ‘ultrasonic waves’.

Taxonomy Level 3: Execution Mode

The final level of the taxonomy exists to differentiate between the mode by which the prostheses executes its desired motion or function. Specifically, prostheses with the most common or generalised execution mode of their actuation mode sub-branch are separated from prostheses with task-specific execution modes. For the Hand-Function and Tool-Function branches, the dominant execution mode of electromechanical and body-powered prostheses is that of a gripper; imitating human grasping in the Hand-Function branch, and tool grasping in the Tool-Function branch. Passive/static prosthesis design in the Tool-Motion branch is dominated by ‘holders’ — clips, clamps, and cups that hold objects or tools of choice. The Hand-Function branch is similar, with the addition of ‘hooks’. Finally,

passive/static prostheses in the Tool-Function branch are all passive or static tools, which, by definition of a tool, are task-specific.

Populating the Taxonomy

In order to populate the taxonomy, upper limb prostheses in history, research, clinical use, art works, and fiction were identified from over 200 years of media. In the case of remade works (e.g. a remade film), adaptations of other media (e.g. a film adaptation of a novel), and sequels, prequels, or spin-off media, only the first instance of a prosthesis was recorded. A total of 174 prostheses were recorded to populate the taxonomy.

5.3.2 Insights into the Design Space of Upper Limb Prostheses

The taxonomy leads to important findings regarding the regions of design space that are occupied by real and fictional upper limb prostheses. First, passive/static devices exist across all four branches of the taxonomy, with varied task-specific designs as commonplace as object- and tool-holder designs. Second, body-powered prostheses are, as previously mentioned, predominantly grippers. Finally, real-world electromechanical prostheses, despite having access to the widest range of actuators and a greater number of controllable degrees of freedom, exhibit little diversity; almost all electromechanical prostheses are multi-articulating hands or grippers, with no examples found of task-specific prostheses of this kind. This is in direct contrast to electromechanical prostheses seen in art and fictional works, which are frequently task-specific and allow characters to complete otherwise impossible tasks. Examples of these include the Chainsaw Arm from the *Evil Dead II* film [Raimi and Spiegel 1987], Inspector Gadget’s hand which can transform into a range of tools [Bianchi et al. 1983], and Ulysses Klaw’s weaponised arm from the Marvel Comics [Lee and Kirby 1966]. Fictional inspiration is often taken when designing multi-articulating myoelectric hands — the LUKE arm [Resnik et al. 2014] received its name in honour of Luke Skywalker’s prosthetic hand from the Star Wars film series [Kershner and Lucas 1980], and the Hero Arm (Open Bionics; UK) is available in a range of styles that mimic fictional prosthetic and robotic hands — making this disparity regarding task-specific hands even more surprising.

5.4 Task-Specific Upper Limb Prostheses

In this section, four terminal devices are presented that serve as illustrative examples of each branch of the taxonomy. Each device is modular, and replaces one finger of the Olympic hand, making use of no-tool-required finger modularity for easy replacement [Liow et al. 2020]. For Hand-Motion the human motion of flicking was recreated: the storing and releasing of mechanical energy through a finger. The flicking device presented in this work enables users to flick with varying levels of strength,

using a the motor input from a single finger of the prosthesis. Flicking is used extensively in social settings, such as the game ‘carrom’, which is played by millions worldwide. For Tool-Motion, the twisting motion required to use a screwdriver is considered; this is an action that is vital in many professions. For an anthropomorphic prosthesis this coordination of multiple fingers to produce fine motion is nearly impossible, but for a non-anthropomorphic device this can be achieved simply, and a twisting device is developed to directly transmit the rotation of a motor to the screwdriver via a gear drive. For Hand-Function, the specific function of grasping flat objects is considered. This is a notoriously challenging task for anthropomorphic prostheses, but this is achieved with a suction cup-based terminal device that can easily pick and place smooth, flat objects. Finally, for Tool-Function, the task of cutting paper is considered, and develop a terminal device that performs this function directly; this device brings fiction to life by reproducing the functionality of the hands of the fictional character ‘Edward Scissorhands’ [Burton 1990].

5.4.1 The OLYMPIC Hand as a Test Platform

The OLYMPIC hand is a modular prosthesis, where each finger of the hand can be removed without the need for external tools [Liow et al. 2020]. When a finger is removed, an interface with the finger’s driving motor is exposed (see Fig. 5.2). The task-specific terminal devices presented in this chapter retarget one or more of these motor DOFs to perform specific tasks or actions. The motor interfaces for the fingers are all in-plane, simplifying terminal device interface and transmission design considerably. All terminal devices were manufactured using 3D printed and commonly available components.

5.4.2 Terminal Device 1: Flicking Motion

The ability to produce a flicking motion is one that is often taken for granted. Used all across the world in social settings such as flipping a coin or taking part in games such as carrom, shove ha’penny, or paper football, flicking forms a part of every day life and has been overlooked by prosthesis designers to date. Flicking with a human finger is the sudden release of stored mechanical energy; although many prostheses do use extension springs which could store energy, the execution of a flicking motion is difficult as it requires the coordination between multiple digits to block and release the extension of one finger. The second terminal device presented in this work is one that imitates the end-effector flicking motion of a human hand, but is achieves this in a non-anthropomorphic way using a single motor input.

The flicking device, shown in Fig. 5.3 a and b, uses two tendons. The first is used to load the ‘striker’ by drawing a pin along a linear ratchet and storing elastic energy. The second tendon is used to release the striker by raising the pin above the teeth of the ratchet where it can move freely. Both tendons are wound around the same ‘dual’ pulley, but in opposite directions; when the draw tendon is in tension, the release tendon is slack, and vice versa. As the release tendon is wound to remove

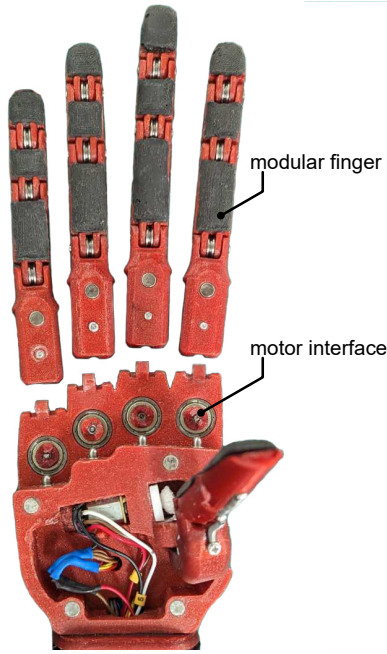


Figure 5.2: The modular base prosthesis used to test each task-specific device. The OLYMPIC hand, the modular test base used to actuate and control each terminal device. Motor interface and modular finger labelled.

slack then actuate the release carriage, the draw tendon becomes slack and accumulates excess tendon length such that, when the pin is released, the striker can move along its full trajectory unhindered. The linear ratchet enables the striker to be loaded to 5 levels of energy storage, enabling users to modulate the impulse transferred to the object that is being flicked.

The striker arm has a length of approximately $L_s = 125.0$ mm, and the pin moves along a line that is $d_h = 53.8$ mm vertically below the axis of rotation of the striker, bringing the striker arm from a rest angle of $\theta_{\min} = -5.0^\circ$ to a maximum draw of $\theta_{\max} = 30.0^\circ$. Given a pin position of x mm from rest, the draw angle can be calculated:

$$\theta_d = \text{atan2}(x + x_0, d_h), \quad (5.1)$$

where x_0 is equal to $d_h \tan(\theta_{\min})$. The elastic cord used to store energy for flicking is attached at one end at a distance $d_e = 62.4$ mm and angle $\theta_e = -11.7^\circ$ from vertical, and at the other end to the tip of the striker. The length of the elastic cord L_e is therefore:

$$L_e = \sqrt{L_s^2 + d_e^2 - 2L_s d_e \cos(\theta_d - \theta_e)}, \quad (5.2)$$

giving a tendon force of $F_e = K(L_e - L_0)$, where K and L_0 are the spring constant and relaxed length of the elastic cord, respectively. Finally, the torque applied to the striker is equal to:

$$\tau_s = F_e L_s \sin(\theta_{es}), \quad (5.3)$$

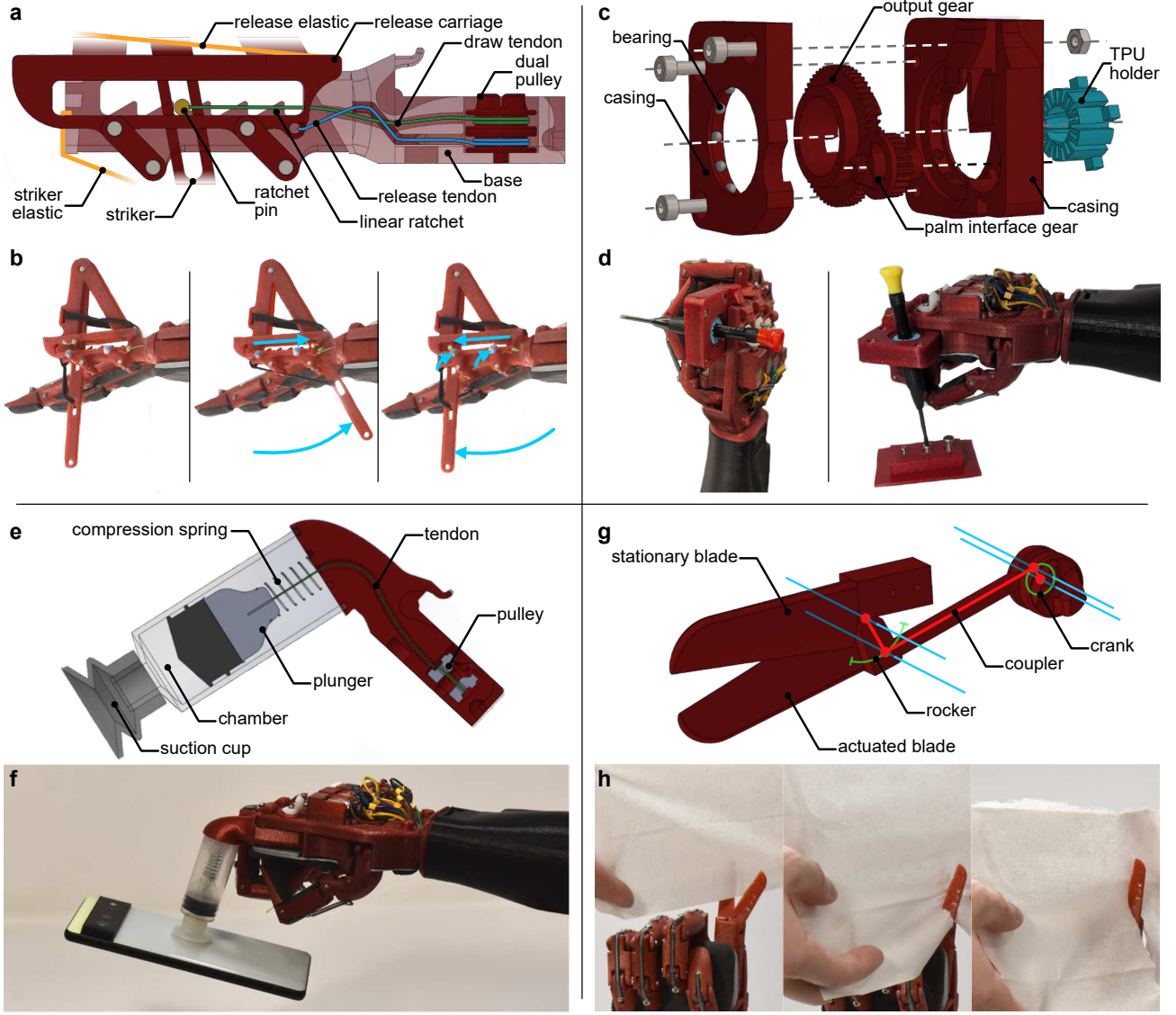


Figure 5.3: Four non-anthropomorphic, task-specific prosthetic terminal devices. **a, b**, Flicking device: section view of the flicking mechanism (**a**), initial, drawn, and released positions of the device (**b**). **c, d**, Twisting device: exploded view of the gear mechanism used to produce testing motion (**a**), a screwdriver mounted in the device and the device being used to screw in a cross-head screw (**d**). **e, f**, Suction device: section view of the spring-release suction cup mechanism (**e**), the suction device holding a mobile phone (**f**). **g, h**, Cutting device: internal view of the crank and rocker mechanism driving the cutting motion (**g**), the device cutting a sheet of tissue paper (**h**).

where θ_{es} is the angle that the elastic cord makes with the striker, calculated using the sine rule:

$$\sin(\theta_{es}) = \frac{d_e}{L_e} \sin(\theta_d - \theta_e).$$

This device is controlled using two surface EMG electrodes placed on the anterior and posterior forearm, respectively. The commanded position of the motor that draws and releases the striker, q_{flick} , is controlled by the difference between the smoothed signals from the two electrodes, $s_1(t)$ and $s_2(t)$. During drawing, the motor position is incremented according to a constant draw rate of $\bar{v}$. To release,

the motor is driven directly to its release position q_{release} , which raises the release carriage:

$$q_{\text{flick}}(t + \Delta t) = \begin{cases} q_{\text{flick}}(t) + \bar{v}\Delta t & s_1(t) - s_2(t) > \bar{s}_{\text{draw}} \\ q_{\text{release}} & s_2(t) - s_1(t) > \bar{s}_{\text{release}} \\ q_{\text{flick}}(t) & \text{otherwise} \end{cases}, \quad (5.4)$$

where $\bar{s}_{\text{draw}}$ and $\bar{s}_{\text{release}}$ are thresholds to ensure the striker is not drawn or released mistakenly, and Δt is the control rate of the prosthesis.

5.4.3 Terminal Device 2: Twisting Screwdriver Motion

The second terminal device presented in this work is a terminal device that produces the twisting motion required to use a screwdriver. As mentioned previously, coordinating the fingers of an anthropomorphic prosthesis to rotate the fingertips around a remote centre of motion is extremely difficult. For a non-anthropomorphic robot, however, this can be achieved in a number of simple ways, such as with a gear, belt, or screw drive. Shown in Fig. 5.3 c and d, Terminal Device 1 utilises a gear drive with gear ratio 1 : 2.4 (12.5 mm : 30 mm), chosen to take advantage of the rest ‘face-down’ orientation of the palm of the prosthesis, meaning the axis of the twisting motion can be coplanar to the motor interfaces on the hand.

In order to control this terminal device, a simple EMG controller based on thresholding was implemented. The commanded torque of the corresponding motor is controlled by the difference between the smoothed signals from the two electrodes, $s_1(t)$ and $s_2(t)$. When the differential signal $s_1(t) - s_2(t)$ rises above a threshold $\bar{s}$, the terminal device motor is driven at maximum torque τ_{max} . Similarly, when the negative differential signal $s_2(t) - s_1(t)$ rises above the same threshold, the motor is driven in reverse:

$$\tau_{\text{scissors}} = \begin{cases} \tau_{\text{max}} & s_1(t) - s_2(t) > \bar{s} \\ -\tau_{\text{max}} & s_2(t) - s_1(t) > \bar{s} \\ 0 & \text{otherwise.} \end{cases} \quad (5.5)$$

5.4.4 Terminal Device 3: Grasping Small, Flat Objects

The third terminal device presented is one that imitates the functionality of the human hand when grasping small, flat objects. The human hand is adept at performing this function, thanks to a complex array of mechanoreceptors that elicit rapid local motor responses during precision manipulation to ensure grasped objects remain held [Johansson and Westling 1987]. Replicating this in an anthropomorphic form is extremely challenging given sensing, actuation, and control limitations, and existing prostheses struggle considerably with precision tasks such as grasping small, flat objects [Resnik et al. 2018; Mohammadi et al. 2022].

This terminal device utilises a suction cup controlled by a tendon-spring actuated plunger. Shown in Fig. 5.3 d and e, a tendon is routed from the palm interface pulley to the plunger, which generates a vacuum inside the chamber. As the plunger retracts, assuming that air behaves as an ideal gas, a pressure differential ΔP is created that is inversely proportional to the expanded volume of the chamber V_1 :

$$\Delta P = P_0 \left(\frac{V_0}{V_1} - 1 \right), \quad (5.6)$$

where P_0 is atmospheric pressure and V_0 is the initial chamber volume.

The vacuum chamber has an internal diameter of $D_v = 21$ mm, and a maximum plunger travel of approximately $q_{\max} = 25$ mm. The terminal device is controlled such that the plunger rests in the middle of the chamber. The soft suction cup is able to passively produce a vacuum when pressed onto the surface of an object, so the plunger must be able to travel beyond its rest position $q_{\text{rest}} = 5$ mm in order to produce a slight positive pressure to counteract the passive vacuum and release the held object. With a plunger diameter of $D_p = 27$ mm and standard conditions of $P_0 = 1.01325$ Pa, and neglecting the volume of air inside the plunger, the maximum suction force F_v that can be produced at the suction cup is:

$$F_v = -A_p P_0 \left(\frac{q_{\text{rest}}}{q_{\max} - q_{\text{rest}}} - 1 \right), \quad (5.7)$$

where $A_p = \pi D_p^2/4$. This gives a theoretical suction force of approximately 43.5 N, or 4.4 kg.

Two surface EMG electrodes are used for control, where the difference between the smoothed signals from the two electrodes, $s_1(t)$ and $s_2(t)$, determines the target position of the plunger:

$$q_{\text{plunger}} = (0.5q_{\max} - q_{\min})(s_1(t) - s_2(t)) + q_{\text{rest}}. \quad (5.8)$$

5.4.5 Terminal Device 4: Cutting Paper

Cutting paper is a task typically performed with a tool—namely scissors—however, producing the motion required to use scissors with a prosthetic hand is very difficult, because it requires each handle to be moved around a remote centre of motion. The final terminal device presented here achieves this same cutting functionality, but the prosthesis itself is the tool.

Shown in Fig. 5.3 g and h, a crank and rocker mechanism is used to convert continuous rotation of the finger interface gear to oscillatory motion of one blade of the scissors, while the other blade remains stationary. With crank, coupler, and rocker link lengths of $l_1 = 3$ mm, $l_2 = 32$ mm, and $l_3 = 7.5$ mm, respectively, and a distance between the crank and rocker axes of $l_4 = 35.5$ mm, the maximum rocker angle relative to horizontal can be computed via the cosine rule:

$$\theta_{\max} = \arccos \left(\frac{l_3^2 + l_4^2 - (l_1 + l_2)^2}{2l_3l_4} \right), \quad (5.9)$$

and the maximum angle:

$$\theta_{\min} = \arccos\left(\frac{l_3^2 + l_4^2 - (l_1 - l_2)^2}{2l_3l_4}\right). \quad (5.10)$$

The scissor blade therefore has a range of motion of approximately 53.3 °.

Because the terminal device produces continuous cutting functionality, control only requires a single surface EMG electrode. When the smoothed signal from the electrode, $s_1(t)$, rises above a threshold $\bar{s}$, the terminal device motor is driven at maximum torque:

$$\tau_{\text{scissors}} = \begin{cases} \tau_{\max} & s_1(t) > \bar{s} \\ 0 & \text{otherwise.} \end{cases} \quad (5.11)$$

5.4.6 Evaluation

Evaluating terminal devices that do not conform to traditional prosthesis design philosophies is challenging. Many dexterity assessments have been designed to evaluate a user’s ability to perform ‘activities of daily living’ [Light et al. 1999], often taking the form of pick and place tasks [Jebsen et al. 1969; Trombly and Scott 1983; Light et al. 2002] or other simple manipulation tasks such as peg insertion [Tiffin and Asher 1948]. For functional terminal devices (Hand-Function and Tool-Function), assessment is relatively straightforward; the user’s ability to perform said function can be quantitatively measured. For motion-based terminal devices (Hand-Motion and Tool-Motion), this can be more difficult. If the targeted motion can be applied to a well defined task, then task performance can be used as a proxy for evaluation purposes. However, prosthesis use goes beyond pure functionality, and longer-term comfort and user preference are extremely important, and therefore further metrics must be considered. In this work two further metrics are used, that have been explored in a number of studies: user perceived task load [Parr et al. 2023] (also explored in Chapters 2 and 4), and the compensatory motion that the user must perform with their body in order to perform a given motion [Hunt et al. 2017; Vujaklija et al. 2023]. Given that the most common reasons for prosthetic hand rejection are discomfort and weight [Salming et al. 2020], monitoring compensatory motion (which can lead to longer-term discomfort) and task load—including perceived physical demand—gives us an important insight into how non-anthropomorphic terminal devices could fare during regular at-home use.

Two groups of participants without upper limb difference were used to evaluate each terminal device: a control group (C group) who used the OLYMPIC hand in its anthropomorphic configuration, and the terminal device group (TD group) who use the OLYMPIC hand with the non-anthropomorphic terminal device. Each participant group that evaluated each device contained 8 participants, the characteristics of which are given in Appendix B, Table B.1. Finally, each device was tested by two participants with upper limb difference as two case studies, the characteristics of whom are

given in Appendix B, Table B.2. This study was given a favourable opinion by the Imperial College Research Governance and Integrity Team (RGIT), number 6571021, which was in accordance with the Declaration of Helsinki. Written consent was obtained from all participants prior to taking part in this study. Participants depicted in figures gave informed consent for their images to be published.

Task Performance

The tasks chosen to evaluate each terminal device corresponded to either the function or a task related to the motion that the terminal device was designed to perform. The flicking device was evaluated with a disk-flicking task; the twisting device with a screwing task; the suction device with the stacking checkers task from the Jebsen-Taylor Hand Function Test [Jebsen et al. 1969]; and the cutting device with a circle cutting task.

Compensatory Motion

Compensatory movement of the user was measured using four 6 DOF Vive Trackers (HTC Ltd.) placed on the trunk, upper arm, and lower arm (see Appendix B Fig. B.1), and a reference tracker placed on the desk at which the user is sitting. Tracker pose information was streamed at 100 Hz, with the x axis of the trackers aligned with the axis of each body part that was tracked. In this chapter the angular deviation of the three trackers from their initial orientation is computed as a proxy for compensatory movement. This is achieved by first computing the relative rotation $R_{0 \rightarrow t}$ between the tracker's initial orientation R_0 and its orientation at time t , R_t :

$$R_{0 \rightarrow t} = R_t R_0^T. \quad (5.12)$$

The magnitude of this relative rotation, θ_t , can be computed

$$\theta_t = \left| \arccos \left(\frac{\text{Tr}(R_{0 \rightarrow t}) - 1}{2} \right) \right|. \quad (5.13)$$

Here, the mean absolute angle over the entire task is taken as a quantification of compensatory movement.

User Perception

To evaluate user perception the NASA Task Load Index (NASA-TLX) questionnaire [Hart and Staveland 1988] was used, and the raw TLX scores of participants [Hart 2006] reported in order to obtain a greater level of detail as to which factors influence perceived task load. In the NASA-TLX questionnaire, participants self report their perceived levels of physical demand, mental demand, temporal demand, performance, effort, and frustration on a 20-point scale (in this study displayed as a numer-

ical value out of 100 in increments of 5). The two participants with upper limb difference were also asked to complete a truncated version of the Prosthesis Embodiment Questionnaire for Upper Limb Prostheses developed in Chapter 4 (questions are listed in Appendix B Table B.3).

5.4.7 Task Setup

5.4.8 Flicking Task

Terminal device 1, which replicates flicking motion, was assessed with a devised disc flicking task, in which participants attempt to flick a disc at one of seven target discs, and success rate is recorded as a performance metric; 35 trials were performed in distance order—five attempts per target, from closest to farthest—after 15 training trials. The flicking task was carried out on a flat whiteboard surface, using the 3D printed 25 mm diameter by 8 mm thick discs from the Jebsen-Taylor Hand Function Test. The target locations are arranged as follows:

- Location 1: radial offset of 100 mm, axial offset of 0mm.
- Location 2: radial offset of 200 mm, axial offset of 150mm.
- Location 3: radial offset of 300 mm, axial offset of 0mm.
- Location 4: radial offset of 400 mm, axial offset of -150mm.
- Location 5: radial offset of 500 mm, axial offset of 0mm.
- Location 6: radial offset of 600 mm, axial offset of 150mm.
- Location 7: radial offset of 700 mm, axial offset of 0mm.

5.4.9 Screwing Task

Terminal device 2, which replicates the twisting motion to use a screwdriver, was assessed via a devised task in which participants screw three different screws (each requiring a different screwdriver) into a test board; this was repeated three times after a single practice trial. The details of this setup are as follows:

- Screw 1: M4 x 10 mm, panhead screw, reset to 8 mm from the test board surface.
- Screw 2: M3 x 10 mm, Phillips screw, reset to 6 mm from the test board surface.
- Screw 3: M2 x 10 mm, Torx T6 screw, reset to 4 mm from the test board surface.

5.4.10 Stacking Task

Terminal device 3, which replicates the functionality of picking up flat objects, was assessed with the stacking checkers task of the Jebsen-Taylor Hand Function Test, where participants stack four checkers on a raised surface as fast as possible [Jebsen et al. 1969]. For all tasks, a single practice attempt was allowed before testing began.

5.4.11 Cutting Task

Finally, terminal device 4, which produces a cutting function, was assessed by asking participants to cut a template 10 cm diameter circle from a sheet of paper, where task completion time and relative circularity were recorded as performance metrics. The edge of each circle was located approximately 25 mm from the edge of the paper. Circularity is defined as 4π times the area of a shape divided by its squared perimeter:

$$circularity = \frac{4\pi \times area}{perimeter^2}, \quad (5.14)$$

and has a maximum value of 1. After participants cut each circle, the circles were imaged (see Appendix B Fig. B.2) and circularity calculated. To account for any perspective differences between images, the template circle was captured in the same image and used as a reference circularity score for the cut circle. The relative circularity was then computed as the circularity of the participant's cut circle to the circularity of the template circle in the same image. Circularity was chosen over other evaluation metrics such as intersection-over-union because circularity is agnostic to the size of the cut shape; some participants chose to cut around the edge of the template circle, while others chose to cut inside the template circle. It was reasoned that participants should not be penalised for this.

5.5 Grasp-Specific Upper Limb Prostheses

In this section, the Hydra Prosthetic Hand is introduced. In the taxonomy of upper limb prostheses shown in Fig. 5.1 a, two highly populated and closely related branches exist. The first contains body-powered gripping prostheses that are highly effective at performing single grasps but lack versatility, making them unable to adapt to new grasps or scenarios. The second contains multi-articulating myoelectric prostheses that are versatile in the grasps and gestures they produce, but perform poorly in tasks and activities, and require a high amount of independently functioning muscle tissue to perform a full range of motions; something that is often not available to many end-users [Uellendahl 2017] (as was the case for many participants in experiments performed in Chapter 4). In the majority of tasks, body-powered prostheses are better performing, with superior task performance observed in Chapter 3, as well as body-powered prostheses winning both the 2016 and 2020 editions of the Cybathlon Arm Prosthesis Race [Capsi-Morales Id et al. 2023; Caserta et al. 2022]. Combining the

effectiveness of a body-powered prosthesis with the versatility of a myoelectric prosthesis could lead to functional benefits, and may make advanced prosthetic technology accessible to end users who are currently unable to make use of existing prostheses.

The Hydra Hand is designed to perform both rigid precision and compliant power grasps via a single body-powered actuation input, and perform a secondary wrist rotation motion from a myoelectric control input. The targeted precision grasp is a two-fingered pinch, which can take the form of a palmar pinch or an inferior pincer [Feix et al. 2016]. For power grasps, reshaping the hand and caging objects in three dimensions becomes more important, so both cylindrical and spherical power multi-finger grasps are targeted. Furthermore, the shape of power-grasped objects can be irregular, therefore a level of adaptability between compliant fingers is necessary to accommodate for this. Here, the mechanical design of the hand of the prosthesis is presented, split into two subsections: the mode-switching mechanism, and the kinematics of the gripper.

The dimensions of the Hydra Hand are modelled on those of an adult male’s hand (see Fig. 5.4 a). Each finger is approximately 95 mm long and has a width and thickness of 20 mm, falling in the range of the average index finger length and average thumb width and thickness. The palm of the Hydra Hand has a diameter of 60 mm, which is designed to match the average distance from the base of the thumb to the base of the index finger on the palmar surface of a human hand. At rest the fingers are at an angle of 30° to each other, giving a fingertip-to-fingertip distance of approximately 140 mm, mimicking the angle and fingertip-to-fingertip distance of a human hand when reaching to grasp a medium-sized object. The hand is comprised of four fingers: two type *A* fingers, and two type *B* fingers (shown in Fig. 5.4 c); the length of the proximal and distal phalanges of the type *A* fingers are 50 mm and 45 mm, respectively, and of the type *B* fingers are 40 mm and 55 mm, respectively.

5.5.1 Mode-Switching

The type *A* fingers of the Hydra Hand are mounted on a static palm section, while the type *B* fingers are mounted on a rotating palm section. The rotating palm section is actuated by a stepper motor, and allows the hand to reconfigure and reshape to achieve a range of grasps between cylindrical and spherical grips. When the rotating palm reaches its limit, adjacent fingers magnetically lock together and produce a precision gripper. The base of each finger is deliberately mounted at a lateral offset from the sagittal plane of the hand, meaning the flexion planes of all four fingers are parallel when the hand is in precision mode. A similar rotating palm is utilised in the Yale Model Q, but is primarily used to perform in-hand rotation of objects, rather than to expand the available grasps of the gripper [Ma and Dollar 2014].

Unlike a human finger, that can flex its proximal and distal joints independently, the Hydra Hand is underactuated, with a single tendon controlling both finger joints. Because it is not possible to purposely position the fingertips such that a fingernail feature on the dorsal side of the finger could

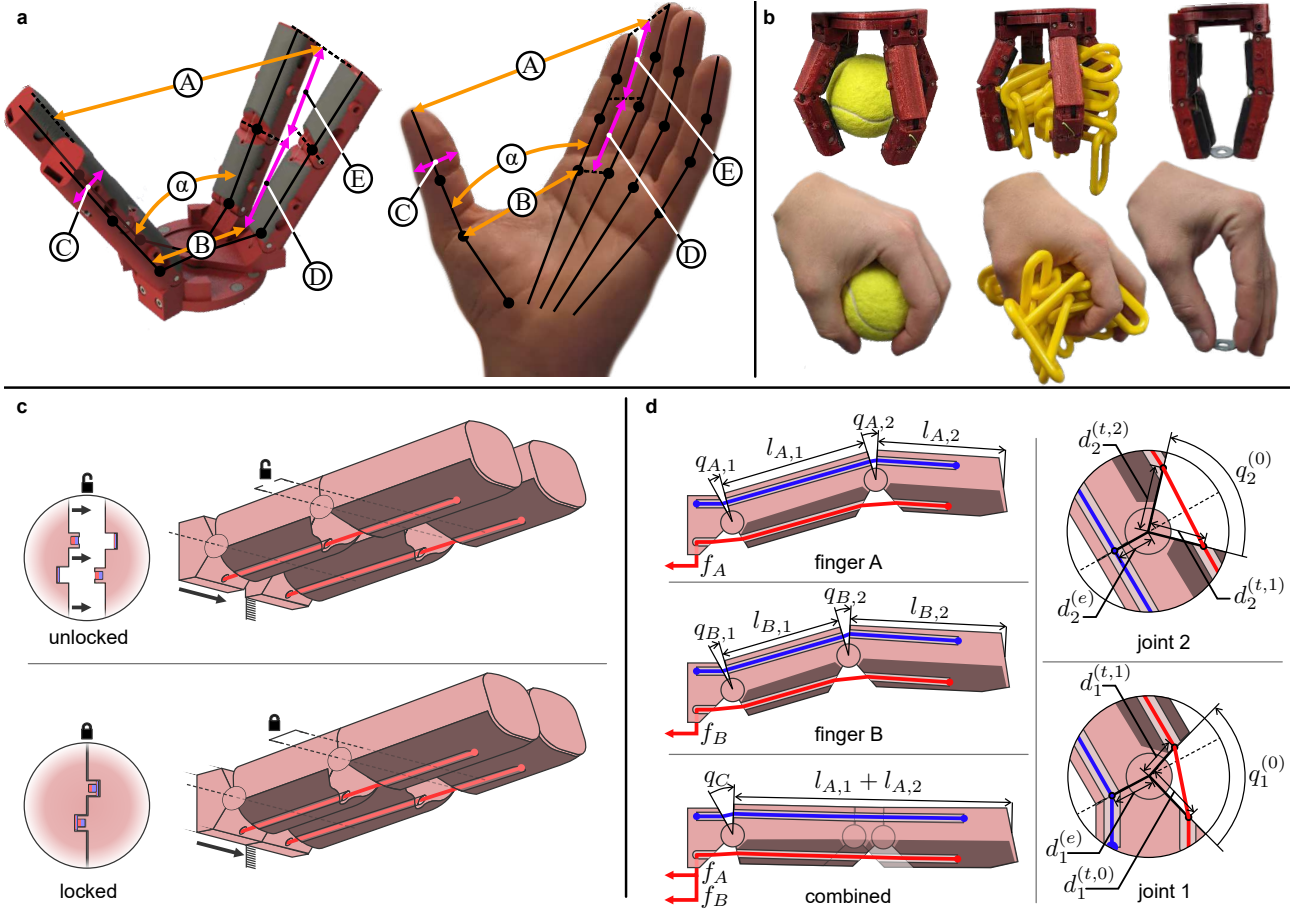


Figure 5.4: The design of a grasp-specific non-anthropomorphic prosthesis: the Hydra Prosthetic Hand. **a**, Key dimensions of the hand, modelled on a human hand. **b**, Grasping capabilities of the Hydra Hand that mimic those of a human hand, grasping a ball, an articulated chain, and a washer.. **c**, The finger locking mechanism of the hand. Flexion axes of the distal joints of each finger are misaligned, and locating magnetic features embedded in each finger prevent relative in-plane rotation and translation of laterally adjacent links. **d**, Schematic diagram of the fingers and joints of the hand. Flexion tendons are shown in red on the palmar side of each finger. Extension elastic cords are shown in blue on the dorsal side of each finger.

be used for a tip pinch grip, the targeted precision grasps are the palmar pinch and inferior pincer grasps. To aide this, a fingernail feature is present on the distal face of the fingertip, allowing the palmar pinch grasp to also serve as a tip pinch.

The motion group of finger A can be described by sequential rotations around joint axes a_1 and a_2 [Rojas and Dollar 2016]:

$$\mathcal{S}_A = \{\mathbf{R}(A_1, a_1)\} \cdot \{\mathbf{R}(A_2, a_2)\}, \quad (5.15)$$

and similarly for finger B , with joint axes b_1 and b_2 :

$$\mathcal{S}_B = \{\mathbf{R}(B_1, b_1)\} \cdot \{\mathbf{R}(B_2, b_2)\}. \quad (5.16)$$

When the rotating palm section reaches its limit, the finger pairs are aligned and passively locked together with raised features and magnetic contacts (see Fig. 5.4 b) to act as a single combined finger

for two-fingered grasping. To switch from compliant fingers to rigid fingers for precision grasping, the distal flexion axes of the fingers are misaligned. The raised features prevent the relative in-plane motion of the adjacent distal links, and therefore constrain the flexion of the distal joints to be zero. The only joint that can therefore be actuated is the combined proximal joint, producing a two-fingered rigid gripper that can perform precision grasps. When finger A and B are combined, the combined finger motion group is the intersection of the two component motion groups, $\mathcal{S}_{A+B} = \mathcal{S}_A \cap \mathcal{S}_B$:

$$\begin{aligned} \mathcal{S}_{A+B} = & (\{\mathbf{R}(A_1, a_1)\} \cdot \{\mathbf{R}(A_2, a_2)\}) \cap \\ & (\{\mathbf{R}(B_1, b_1)\} \cdot \{\mathbf{R}(B_2, b_2)\}). \end{aligned} \quad (5.17)$$

The laterally adjacent links of A and B are rigidly connected, and axes a_1 and b_1 are aligned, therefore $\{\mathbf{R}(A_1, a_1)\} = \{\mathbf{R}(B_1, b_1)\}$ and $\mathcal{S}_{A+B} = \{\mathbf{R}(A_1, a_1)\}(\{\mathbf{R}(A_2, a_2)\} \cap \{\mathbf{R}(B_2, b_2)\})$. Since a_2 and b_2 are parallel but offset, $\{\mathbf{R}(A_2, a_2)\} \cap \{\mathbf{R}(B_2, b_2)\} = \{\mathbf{I}\}$ is identity displacement. The combined motion group of displacement is therefore:

$$\mathcal{S}_{A+B} = \{\mathbf{R}(A_1, a_1)\}. \quad (5.18)$$

In the direction perpendicular to the flexion plane of the fingers, the fingers are only held in contact by the attractive forces of the magnets; these forces are not large and allow the fingers to be unlocked by reversing the direction of the rotating palm unit. This simple mechanism allows the hand to switch from compliant power grasps to rigid precision grasps and vice versa without any dedicated hardware changes.

5.5.2 Gripper Kinematics

During power grasping, the fingers of the hand are underactuated, with a single tendon driving two flexion joints of each finger, and elastic cord passively driving the extension of both joints (see Fig. 5.4 c). The tendon is routed inside each finger such that it directly acts on each joint, rather than being routed around a joint pulley. The underactuation of each finger enables the hand to be compliant—if the proximal joint gets blocked then the distal joint is free to continue closing. The retractable tendon length $L_{f,j}^{(t)}$ of joint j of finger f can be found using the cosine rule with joint angle $q_{f,j}$ and, with reference to Fig. 5.4 c, tendon routing points at perpendicular offsets of $d_{j,l}^{(t)}$ on link l and $d_{j,l-1}^{(t)}$ on the preceding link, with an offset angle of $q_j^{(0)}$:

$$L_{f,j}^{(t)} = \sqrt{d_{j,l}^{(t)2} + d_{j,l-1}^{(t)2} - 2d_{j,l}^{(t)}d_{j,l-1}^{(t)} \cos(q_j^{(0)} - q_{f,j})}, \quad (5.19)$$

with a similar formulation for the extendable cord length $L_{f,j}^{(e)}$, noting that (see Fig. 5.4 joint view) the perpendicular offset of the routing point of the elastic cord is identical for both links at $d_j^{(e)}$, and

there is zero initial angular offset:

$$L_{f,j}^{(e)} = d_j^{(e)} \sqrt{2(1 - \cos(q_{f,j}))}. \quad (5.20)$$

The perpendicular distance of the tendon to the joint, $L_{f,j}^{(t,\perp)}$ can be found using the angle $\alpha_{j,l}^{(t)}$ that $d_{j,l}^{(t)}$ makes with the tendon, $L_{f,j}^{(t,\perp)} = d_{j,l}^{(t)} \sin(\alpha_{j,l}^{(t)})$, where $\sin(\alpha_{j,l}^{(t)})$ can be found using the sine rule:

$$\sin(\alpha_{j,l}^{(t)}) = \frac{d_{j,l}^{(t)}}{L_{f,j}^{(t)}} \sin(q_j^{(0)} - q_{f,j}). \quad (5.21)$$

This results in a perpendicular tendon distance of

$$L_{f,j}^{(t,\perp)} = \frac{d_{j,l}^{(t)^2}}{L_{f,j}^{(t)}} \sin(q_j^{(0)} - q_{f,j}), \quad (5.22)$$

and a similar result can be found for the perpendicular distance of the elastic cord $L_{f,j}^{(e,\perp)}$:

$$L_{f,j}^{(e,\perp)} = \frac{d_{j,l}^{(e)^2}}{L_{f,j}^{(e)}} \sin(q_{f,j}). \quad (5.23)$$

When the tendon is stationary, the fingers will move to the position of minimum energy. Neglecting gravitational potential energy, the elastic potential energy stored in the elastic extension cord mounted on the dorsal side of the finger is the driving factor in the stable joint-space configurations of the finger. The change in elastic potential energy from the initial position of the finger ($L_{f,1}^{(e)} = L_{f,2}^{(e)} = 0$) can be computed given spring constant $k_f^{(e)}$:

$$E_f^{(e)} = \frac{1}{2} k_f^{(e)} (L_{f,1}^{(e)} + L_{f,2}^{(e)})^2. \quad (5.24)$$

Fig. 5.5 shows the joint space of a finger of the Hydra Hand, with lines of constant tendon length shown, coloured according to normalised elastic potential energy. As seen, the minimum-energy joint-space trajectory of the finger is such that $q_{f,1}$ is minimised until $q_{f,2}$ reaches its joint limit—this is useful for caging objects—however, also seen is another region of minimum-energy is when $q_{f,2}$ is minimised, indicating that bistable grasping behaviour could be achieved with small design alterations. Bistable mechanisms have been used in literature to produce secure, low actuation energy grasps [Stavenuiter et al. 2017; Mouazé and Birglen 2022], and there is scope for future work to explore this for the Hydra Hand. Many underactuated grippers balance the extension springs such that the proximal joints are energetically favourable to actuate, meaning a precision/parallel grasp is the default behaviour of the gripper, and the distal joints do not flex until the proximal phalanges are physically blocked by a grasped object [Ciocarlie et al. 2014]. This form of compliance is favourable when grasping rigid

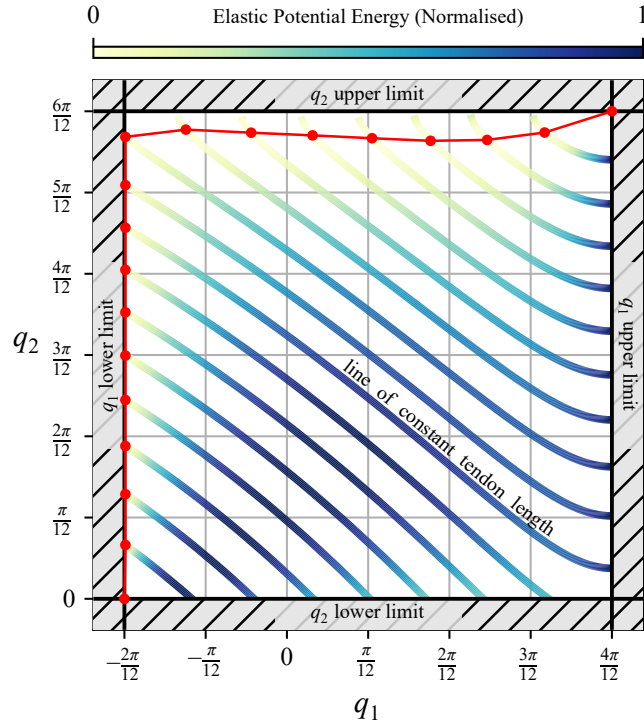


Figure 5.5: Joint space of an individual finger of the Hydra Prosthetic Hand, with joint limits and lines of constant tendon length shown. Lines of constant tendon length are coloured according to the amount of stored elastic potential energy in the elastic extension cord, with lighter showing less energy, and darker showing more energy (normalised per line). The minimum-energy unhindered joint-space trajectory of a finger is shown from rest $(-\frac{\pi}{6}, 0)$ to maximum flexion $(\frac{\pi}{3}, \frac{\pi}{2})$ in red.

objects, but may not be suitable for delicate or articulated objects, where caging the object via form closure may be a safer solution.

5.5.3 Evaluation

The Hydra Hand was evaluated on the YCB Gripper Assessment Benchmark [Calli et al. 2015] in each of its three grasping configurations: precision pinch grasp, cylindrical power grasp, and spherical power grasp. The benchmark consists of 28 objects grasped a total of 136 times - each rigid object is grasped in a series of positions selected from the following: $\mathcal{O}$ (aligned with the gripper), Δx , Δy , and Δz (offset by 1 cm in the x , y , and z directions, respectively). This was repeated for each grasping mode, giving a total of 408 attempted grasping actions. The objects included in the benchmark can be seen in Fig. 5.6 (a).

To quantify the Hydra Hand’s ability to grasp deformable objects, three of the Soft Object Gripper Benchmarks [Clark et al. 2023] were performed: ‘A) flat edge grasp success and drag placement accuracy’, ‘C) crumpled object encapsulation’, and ‘D) flat non-boundary grasp success’. These were chosen to capture both precise and power grasping ability. Benchmark ‘B) edge grasp resilience’ was not performed, as it is a measure of grasping force, rather than the ability to grasp. The items of clothing used in this benchmark are shown in Fig. 5.6 (b), and 330 attempted grasps were performed

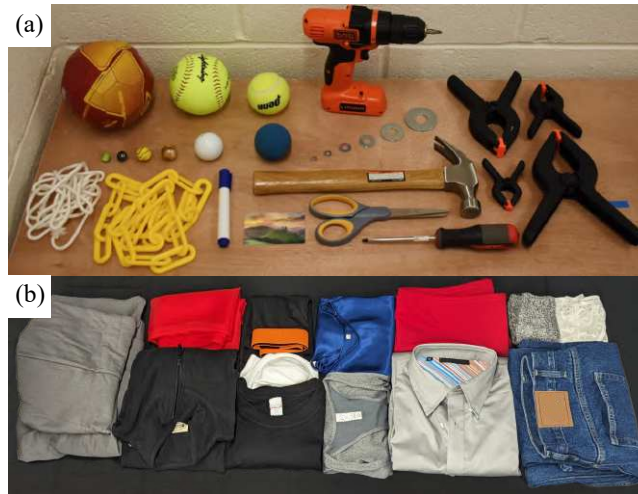


Figure 5.6: Objects used for the YCB Gripper Assessment Benchmark (a) and Soft Object Gripper Benchmarks (b).

in total.

5.6 Results

5.6.1 Task-Specific Devices

Non-anthropomorphic Terminal Devices Outperform Anthropomorphic Terminal Devices

The results of the four tasks can be seen in Fig. 5.7, which highlight the effectiveness of the non-anthropomorphic devices. In all tasks, the anthropomorphic prosthesis was outperformed by its non-anthropomorphic counterpart. It can be seen that non-humanoid users were over 50% more accurate at the targeted flicking task (shown in Fig. 5.7 a), achieving an average hit rate of 0.650, compared to the control group’s average hit rate of 0.429. On the screwing task (see Fig. 5.7 b), the non-humanoid group were considerably faster than the group using the humanoid prosthesis, with average completion times of 278.6 and 701.2 seconds, respectively. Non-humanoid users were able to complete the stacking checkers task of the JTHFT in under half the time of those using the humanoid hand (see Fig. 5.7 c), with mean task completion times of 30.3 seconds and 77.1 seconds, respectively. On the circle cutting task (see Fig. 5.7 d), participants using the anthropomorphic device were over four times slower on average than the group using the cutting device, taking 351.6 and 83.2 seconds to complete the task, respectively. Furthermore, the circles cut by the non-humanoid group were significantly more accurate (images of cut circles are shown in Appendix B Fig. B.2), with an average relative circularity of 0.91 compared to the anthropomorphic group at 0.83 ($p < 0.001$, Mann-Whitney U test).

The task performance of the two participants with ULD generally align with those of the non-humanoid group. On the flicking task (Fig. 5.7 a), Participant 1 was somewhat better than the

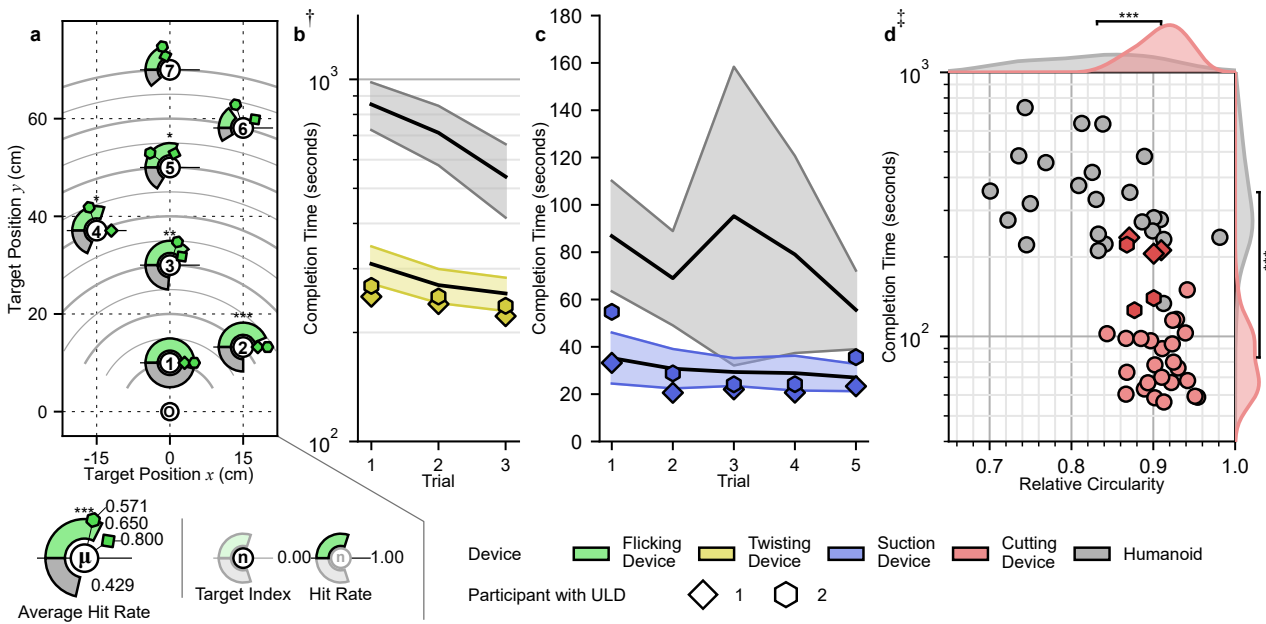


Figure 5.7: Non-anthropomorphic terminal devices improve user task performance. **a** Performance of participants using the Flicking Device and the control prosthesis on a disc flicking task. Scale diagram of flicked disc location (○), target disc locations (1–7), with corresponding hit rates shown. **b** Mean task completion time of participants using the Twisting Device and the control prosthesis on a screwing task. Shaded areas show ± 1 standard deviation. **c** Performance of participants using the Suction Device and the control prosthesis on the stacking checkers task of the JTHFT. Shaded areas show ± 1 standard deviation. **d** Performance of participants using the Cutting Device and the control prosthesis on a circle cutting task: scatter plot of relative circularity of the cut circle (1.00 indicates a perfect circle) against task completion time, with kernel density estimate plots of circularity and completion time shown adjacent to each axis. Results of (a) paired z -tests, (d) paired two-tailed Mann-Whitney U tests: $*p < 0.05$, $**p < 0.01$, and $***p < 0.001$. † The screwing task was completed by Participant 1 with the assistance of a carer, as it was a bimanual task. ‡ The cutting task is a bimanual task; Participant 1 used their left residual limb (above elbow) to hold and manoeuvre the paper that was cut.

participant group, with an average hit rate of 0.80; possibly due to their considerable experience playing a similar flicking game prior to acquiring their limb difference. Participant 1 is a bilateral amputee, with a transhumeral amputation on their left arm. This made the cutting task (Fig. 5.7 d) difficult, as they used their left residuum to manoeuvre the paper during cutting, and led to a longer completion time than the non-humanoid group, although Participant 1 was still faster than the majority of the humanoid group. Similarly, the screwing task (Fig. 5.7 b) was impossible without a second arm, and was completed with the assistance of a carer, producing a slightly faster average completion time of 237.6 seconds than the non-humanoid group.

Non-anthropomorphic Terminal Devices Reduce Compensatory Motion

The mean absolute angular deviation of each body-mounted tracker—the locations of which are shown in Fig 5.8 e—across each task is shown in Fig. 5.8 a-d. During the flicking task, because the control group utilised the extension springs of the index finger of the OLYMPIC hand, a considerable amount

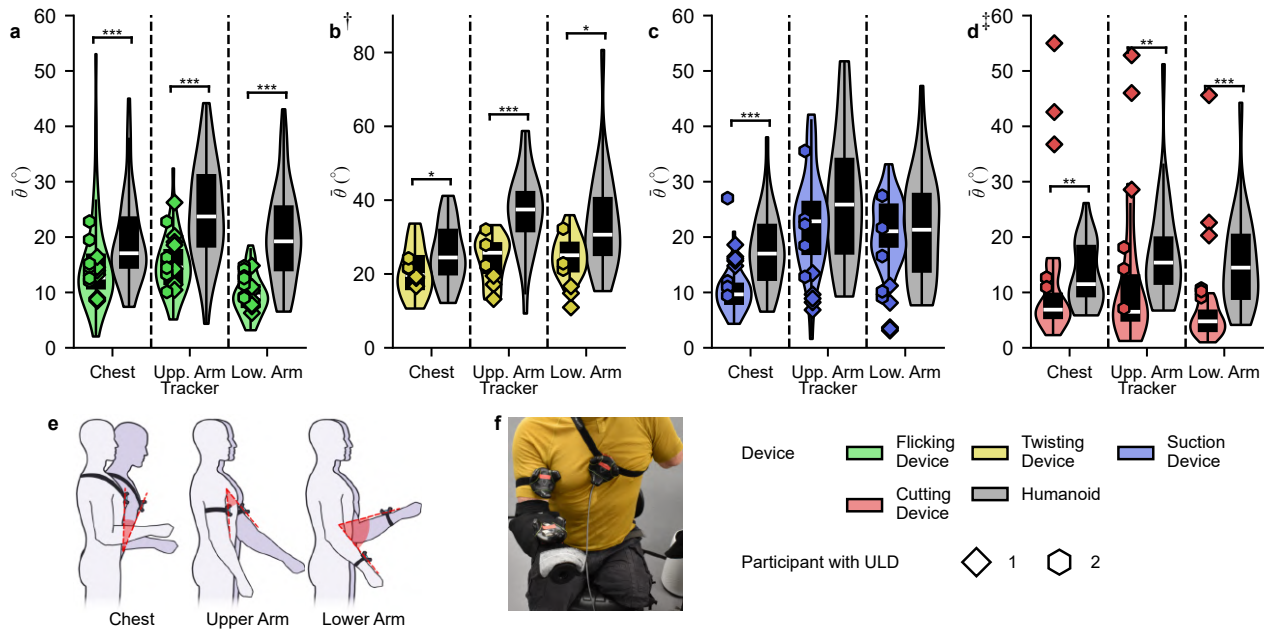


Figure 5.8: Reduced compensatory motion with non-anthropomorphic terminal devices. **a-d**, Mean absolute angular deviation θ of participants using the Flicking Device and the control prosthesis on a disc flicking task (**a**), the Twisting Device and the control prosthesis on a screwing task (**b**), the Suction Device and the control prosthesis on the stacking checkers task of the JTHFT (**c**), and the Cutting Device and the control prosthesis on a circle cutting task (**d**). Results of paired two-tailed Mann-Whitney U tests: * $p < 0.05$, ** $p < 0.01$, and *** $p < 0.001$ (**a-d**). **e** Diagrams illustrating the locations of 6-DOF pose trackers on the body of each participant, and the angular deviation from rest computed at each timestep. **f** Trackers worn by Participant 1. † The screwing task was completed by Participant 1 with the assistance of a carer, as it was a bimanual task. ‡ The cutting task is a bimanual task; Participant 1 used their left residual limb (above elbow) to hold and manoeuvre the paper that was cut.

of manoeuvring was required to load and release the finger to produce a flicking motion. This is visible in Fig. 5.8 a, where the angular deviations of all three trackers were significantly greater than the non-humanoid group ($p < 0.001$ for all three trackers, Mann-Whitney U test). The screwing task required very little arm or torso motion to complete for the participant group using the twisting device, except for during screwdriver changes. The control group, due to an unavoidable radial offset of the held screwdriver axis from pronation/supination axis of the prosthesis, required considerably more compensatory motion to keep the tip of each screwdriver engaged with its respective screw (see Fig. 5.8 b), and the angular deviation of all three trackers are greater for the control group than for the non-humanoid group. The suction device—tested on the stacking checkers task—also reduced the amount of compensatory movement required by the torso and upper arm to complete the task, corresponding to a respective reduction in mean absolute angular deviation of 42.7% and 16.1% compared to the control group (see Fig. 5.8 c). This is because the control group had to manually drag the checkers away from the stacking platform so that they could be grasped on all sides, requiring chest and upper arm motion, whereas the non-humanoid group could pick and place the checkers directly from above. For the cutting task, participants in the control group exhibited a higher amount of compensatory motion while completing the task; this was because the humanoid hand not able to

actuate the scissors, so participants manually pressed the scissors against the table to complete the task. This manual arm motion is reflected in the increase in angular deviation of all three trackers, shown in Fig. 5.8 d.

Again, results of the two participants with ULD generally align with those of the non-humanoid group. As mentioned previously, Participant 1 used their left residuum to manoeuvre the paper during cutting and also used the table for further support. This resulted in a large increase in angular deviation of the chest, upper arm, and lower arm compared to the non-humanoid group (Fig. 5.8 d). Meanwhile, Participant 1 completed the screwing task with the assistance of a carer, meaning that there was a corresponding reduction in compensatory motion (Fig. 5.8 b).

Task Load is Reduced when Using Non-Anthropomorphic Prostheses

Participant responses to the mental demand, physical demand, perceived performance, and frustration questions of the NASA-TLX questionnaire are shown in Fig. 5.9 (responses to all questions are shown in Appendix B Fig. B.3). Mental demand (Fig. 5.9 a) is consistently lower for the non-humanoid group, with the largest differences between the non-humanoid group and the control group observed for the screwing and cutting tasks. A similar trend is seen for physical demand (Fig. 5.9 b), with the largest differences in group responses also being those for the screwing and cutting tasks. Although all tasks were relatively simple in terms of the action performed, these tasks had the longest completion times, exacerbating mental and physical fatigue. Perceived performance (Fig. 5.9 c) is a combination of several factors, but it is observed that the presence of performance-indicative physical cues play a large role. The flicking task (with visible hit or missed discs) and the cutting task (with visible shape and uniformity of the cut object) were the two tasks with the most dramatic differences in perceived performance; the respective median responses of the non-humanoid group and the humanoid group were 65 and 35 for the flicking task, and 85 and 50 for the cutting task. A similar trend can be seen in user frustration (Fig. 5.9 d), however physical and mental demand appear to play a considerable role as well, with the highest frustration occurring when mental and physical demand are high and perceived performance is low.

For participants with upper limb difference, physical demand is generally higher than those in the non-humanoid group. This echoes results observed in Chapter 4, and is due to the combination of infrequently exercised muscles being used for myoelectric control and the weight of the prosthesis concentrated on the participant's residual limb. As expected, the cutting task elicited greater mental demand and frustration, and reduced perceived performance for Participant 1, due to the complexities faced completing the task as a bilateral amputee. An opposite effect was observed for the screwing task, because it was completed with assistance. For Participant 2, frustration was strongly related to perceived performance and physical demand, evidenced by high frustration for the flicking and cutting tasks. Responses to the embodiment questionnaire are shown in Fig. 5.10, showing encouraging

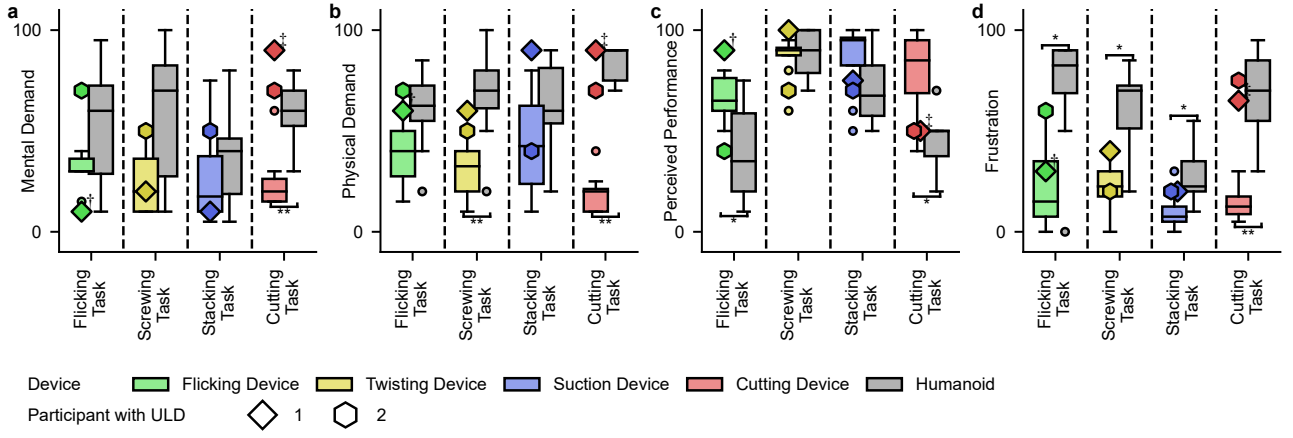


Figure 5.9: Non-anthropomorphic devices reduce task load in users. Raw TLX responses to **a** mental demand, **b** physical demand, **c** perceived performance, and **d** frustration for each device on their corresponding task. Fl. - flicking disc task, Sc. - screwing task, St. - stacking task, and Cu. - cutting task. All plots show results of paired two-tailed Mann-Whitney U tests: * $p < 0.05$, ** $p < 0.01$. † The screwing task was completed by Participant 1 with the assistance of a carer, as it was a bimanual task. ‡ The cutting task is a bimanual task; Participant 1 used their left residual limb (above elbow) to hold and manoeuvre the paper that was cut.

results on ability-related statements (9 and 10), and mixed results on posture and movement quality statements (7, 8, and 11), the latter being anecdotally related to the orientation of the terminal device with respect to a human hand performing the same task. Ownership, embodiment, and body incorporation statements (1 to 6) were generally negative, however—given the short nature of this study—this expected regardless of the form of the terminal device. A longitudinal study is required to study embodiment in depth with regards to non-anthropomorphic upper limb prostheses.

5.6.2 Grasp-Specific Prosthetic Hand

The Hydra prosthetic hand was tested mechanically as a robotic gripper using the YCB Gripper Assessment Benchmark and the Soft Object Gripper Benchmark. The results of the YCB Gripper Assessment Benchmark are shown in Fig. 5.11. As expected, the two compliant power grasping modes fail to grasp small and flat objects, while the precision grasping mode fails to grasp irregularly shaped tool objects. Individually, the precise, cylindrical, and spherical grasping modes achieve scores of 175/404, 132.5/404, and 140/404, respectively. Together, the combined score of the Hydra Hand is 257.5/404 (where the result for each object is taken as the best from the three grasping mode results) — comparable to the Yale Model B gripper [Backus and Dollar 2018], also utilising a single grasping actuator. Fig. 5.12, Fig. 5.13, and Table 5.1 show the results of the Soft Object Gripper Benchmarks A, C, and D, respectively. Benchmark A, where the gripper must grasp cloth edges and drag the item of clothing 500 mm horizontally, and Benchmark D, where each garment was grasped from a central featureless region, were completed using the precision grasping mode. Benchmark C, where crumpled items of clothing are grasped then raised until completely lifted from the table surface, was completed

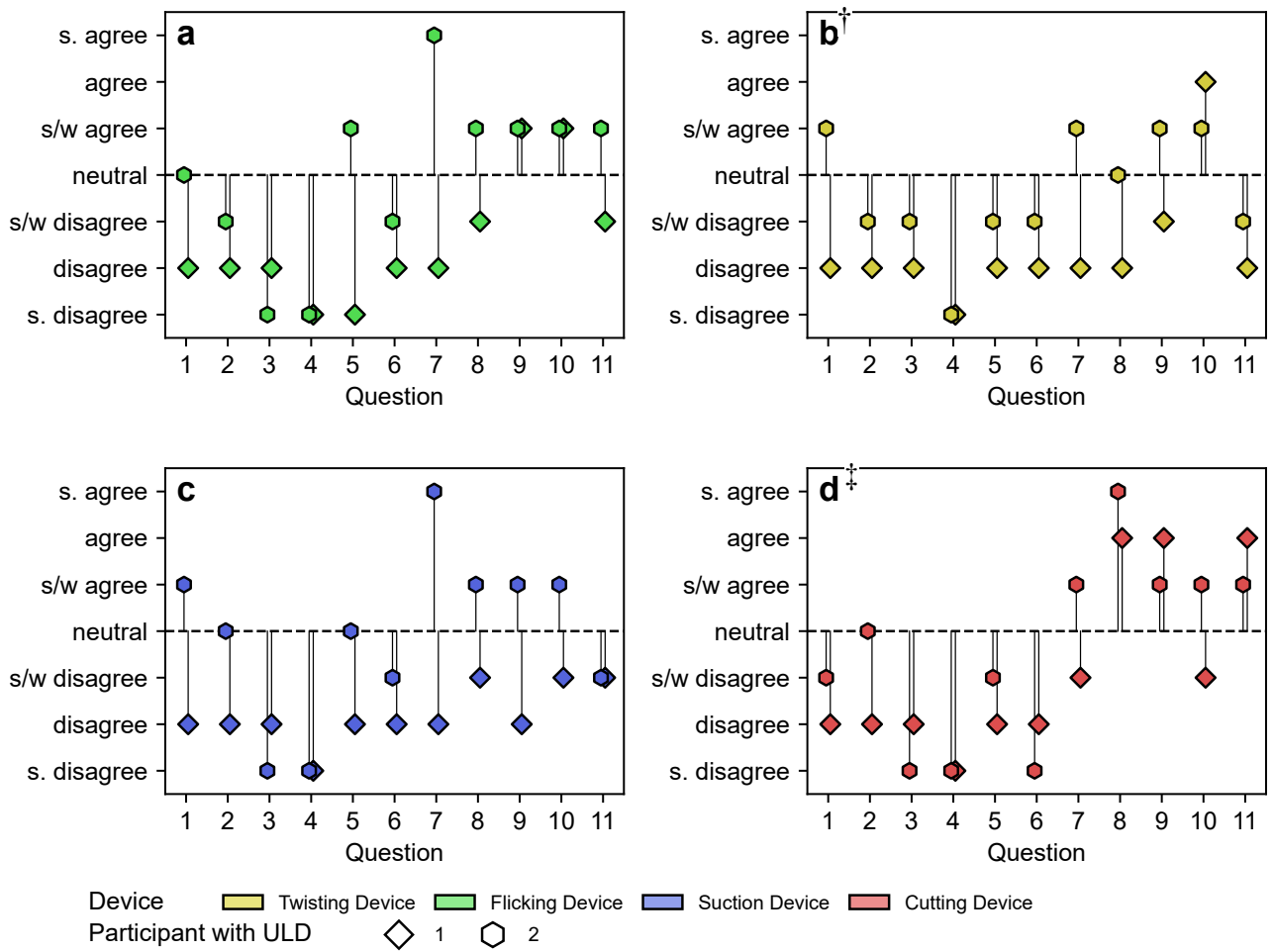


Figure 5.10: Responses of participants with upper limb difference to the embodiment questionnaire after each task. **a** Disk flicking task, **b** screwing task, **c** the stacking checkers task of the Jebsen Taylor Hand Function Test, and **d** circle cutting task. Questions were answered on a 7-point Likert scale after completing each task; full list of questions is given in Appendix B Table A.3. † The screwing task was completed by participant 1 with the assistance of a carer, as it was a bimanual task. ‡ The cutting task is a bimanual task; participant 1 used their left residual limb (above elbow) to hold and manoeuvre the paper that was cut. Abbreviations: s/w - somewhat, s. - strongly.

using the spherical power grasping mode.

The precision mode was successful in grasping the majority of small and flat objects in the YCB Gripper Assessment Benchmark (see Fig. 5.11) and was able to grasp all single, double, and folded edges in the Soft Object Gripper Benchmark A (see Fig. 5.12), as well as successfully grasping nearly all clothes at a central featureless region in Soft Object Gripper Benchmark D (see Table. 5.1). However, some failure cases were observed. The first case was when the object was too small in height, such as the smallest three washers of the YCB Gripper Benchmark. The fingertips of the gripper have a ‘fingernail’-style feature, which is a rigid lip designed to guide objects upwards into the hand by a small amount, however this fingernail has a finite thickness and it was not possible to exploit this feature when grasping small, flat objects. The second case was when grasping heavier objects and stiffer materials. Because only the proximal joint is active during precision mode, the achievable

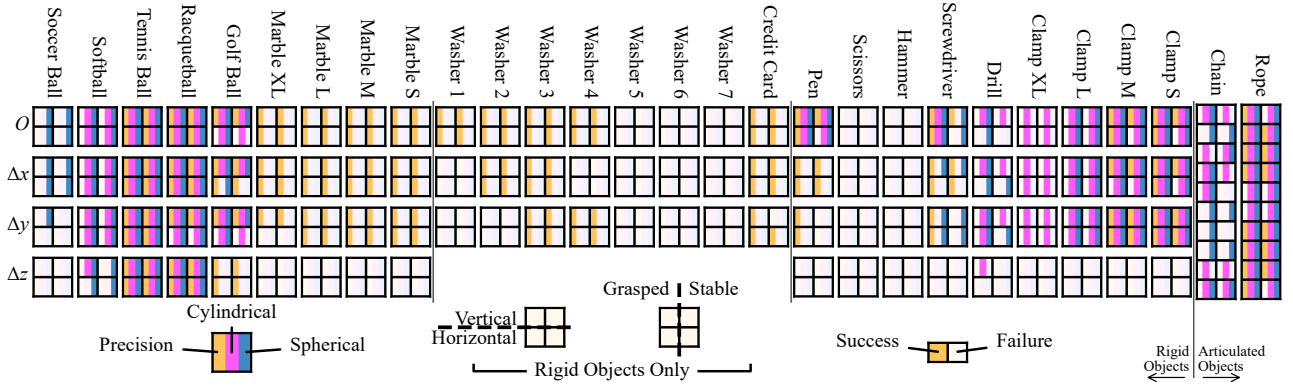


Figure 5.11: Results of the YCB Gripper Assessment Benchmark. For rigid objects, in each 2×2 square, cells are coloured dark or light according to respective success or failure according to the following criteria: top left if a successful grasp is achieved in the vertical orientation, top right if the object is static for 3 seconds after being grasped from above, bottom left if the object remains held while rotated to horizontal, and bottom right if the object is completely static for 3 seconds after being rotated. This was repeated at an origin point O , and at 1 cm offsets Δx , Δy , and Δz . For articulated objects, there are 20 cells showing attempted grasp success or failure, coloured dark or light accordingly. Each cell is divided according to grasp mode used: precision, cylindrical, and spherical modes are shown in orange, magenta, and blue, respectively.

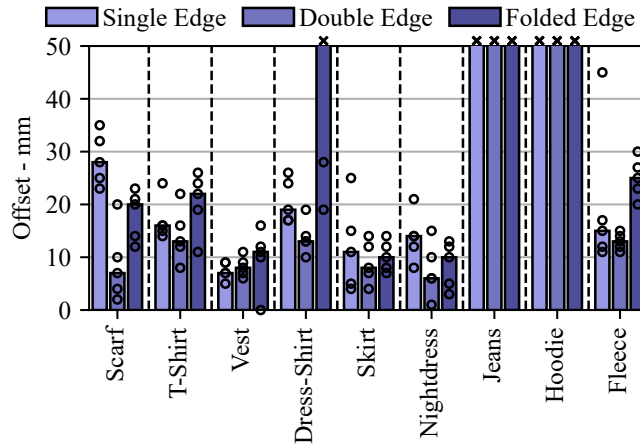


Figure 5.12: Results of the Soft Object Gripper Benchmark A. Items of clothing are grasped and dragged 500 mm horizontally, and placement error is measured. Results for single, double, and folded edges are shown. Bars show median result, $\circ$ and $\times$ marks show successful and failed attempts, respectively.

grasping force of the gripper is reduced compared to the compliant modes, and objects located at the distally will require more actuation force. For example, grasping the largest washer at any offset, grasping central regions of the denim jeans, and dragging the grasped edges of the hoodie and jeans were not possible with the Hydra Hand. In practice, grasping strategies to bring the objects closer to the palm can be used to negate this. In precision mode, adaptive grasping between pairs of fingers is removed to produce a repeatable central grasp. This was especially important when grasping edges of clothing, where it is difficult to predict when one finger will contact the garment. Had adaptive grasping been utilised, premature contact would have allowed the non-contacting finger to move past the target grasping point. Due to the mechanical tolerances required for the raised locking features

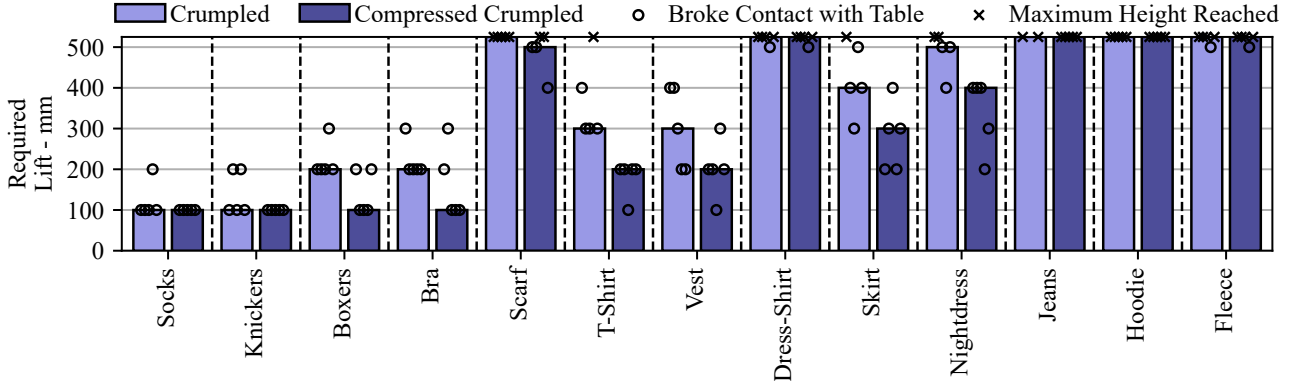


Figure 5.13: Results of the Soft Object Gripper Benchmark C: items of clothing are crumpled, then grasped and lifted until contact with the table is completely broken. Lift height required to break contact with the table (of successful grasps) is shown; Bars show median result, $\circ$ and $\times$ marks show lifts that did and did not break contact with the table, respectively. Note that the Hydra Hand failed to grasp the jeans 3/5 times in the crumpled state.

Socks	Knickers	Boxers	Bra	Scarf	T-Shirt	Vest	Dress-Shirt	Skirt	Nightdress	Jeans	Hoodie	Fleece
1.0	1.0	1.0	1.0	1.0	0.8	1.0	0.8	1.0	1.0	0.0	1.0	1.0

Table 5.1: Results of the Soft Object Gripper Benchmark D. Items of clothing are grasped at a flat, non-boundary region, and grasp success rate is recorded.

to easily connect and disconnect during locking and unlocking, a slight amount of flexion of the distal finger joints was observed in precision mode. This slight flexion was negligible and did not impair precision grasping.

The cylindrical mode was only used in the YCB Gripper Assessment Benchmark (see Fig. 5.11), and excelled at grasping irregularly shaped tool objects (the clamps), and mid-sized spherical objects. Some failures in this mode were observed when a large force was exerted along the axis of the cylindrical grip, for example when the drill was rotated. A further failure mode occurred when the fingers reached their grasping point at a higher position above the grasping surface, limiting the grasps of objects with smaller heights such as the pen, scissors, and screwdriver. This occurs because the distal joint of the fingers flex first, and the fingertips sweep through to meet at a point above the surface.

Spherical mode was used in both the YCB Gripper Assessment Benchmark (see Fig. 5.11) and Soft Object Gripper Benchmark C (grasping crumpled clothes, see Fig. 5.13). This grasping mode, as expected, was successful at grasping round objects, and was also able to grasp irregularly shaped tools with a similar proficiency to the cylindrical grasp. Failure occurred during round object grasping when the objects were smaller than the caging shape of the gripper, such as the golf ball. Here, the golf ball was grasped with the fingertips and lifted successfully, but rolled within the gripper during rotation. This occurred because the fingertips have relatively low friction, and the fingertip force

exerted on the object has a component that acts towards the palm of the hand — this is balanced when the hand is above the object, but during rotation the object is effectively pushed into the hand. For larger objects, spherical grasp enabled greater form closure of the drill than cylindrical mode, meaning the drill could be rotated stably. In spherical mode, the height at which the fingertips meet is lower than in cylindrical mode. This is because the fingers are offset laterally and therefore the plane in which they flex does not pass through the centre of the gripper. In spherical mode, the planes intersect earlier into the flexion motion, meaning that the point at which the fingertips meet is closer to the grasping surface. This allowed the gripper to pick up the screwdriver successfully, which was not possible in cylindrical mode. Spherical mode was successful at grasping and lifting every item of clothing except the jeans in a crumpled state. Similar to the issue faced when grasping the jeans in precision mode, the weight and stiffness of the material made it difficult to grasp the jeans unless a graspable feature was already present; it was difficult to deform the jeans with the gripper to create graspable features. In the compressed crumpled state, there are a higher density of graspable features on the item of clothing, enabling grasping.

The challenging manipulation task of grasping a bunch of grapes then picking a single grape was performed as a pilot task to demonstrate the versatility of the Hydra Hand. Shown in Fig. 5.14 a-b, the bunch of grapes was caged using spherical grasping mode, then placed at a secondary location. Once placed, a single grape was picked from the bunch using the precision grasping mode with a hard coded twist-and-pull action performed by the robot arm. To grasp a delicate, articulate object such as a bunch of grapes is challenging for many grippers, and is only possible because of the energetically favourable flexion motion of the distal joints of the fingers, which allows the gripper to cage objects without exerting excess forces on them. Picking a single grape from the bunch is also challenging, requiring precise motion of the fingers of the gripper to not disturb other grapes in the bunch and to hold the grape firmly enough to pick it, but not so hard that it crushes the grape.

Finally, the Hydra Hand was briefly end-user tested as a prosthetic hand. Seen in Fig. 5.14 c, an end-user grasped a screw-cap bottle, and used their opposing hand to screw the cap on to the bottle.

5.7 Discussion

The taxonomy presented in this work encourages the development of new, non-humanoid prostheses that purposely blur the line between hand and tool. The framework expands the scope of upper limb prostheses beyond hands that perform gripping and gesturing actions, unlocking functional prostheses that can perform a wide range of tasks. Naturally, designing a prosthesis for a given scenario can lead to multiple valid solutions, each occupying a different zone of the framework. As an example, consider designing a prosthesis to allow a user to eat. In the Hand-Motion branch, a device may imitate the natural stabilisation of the hand and wrist, allowing food to be oriented towards the mouth. In the



Figure 5.14: A demonstration of the Hydra Hand on a challenging manipulation task and in use as a prosthetic hand. **a** Using spherical mode to grasp a bunch of grapes via caging. **b** Using precision mode to pick a single grape from the bunch. **c** The Hydra Prosthetic Hand being used to grasp a bottle of water by an end user.

Tool-Motion branch, the pinching action required to use chopsticks may be imitated. In the Hand-Function branch, the hand could be considered a gripper, where the secure holding of an item of food is important. Finally, when only considering the functional aspect of eating, a prosthesis may be designed according to the Tool-Function branch to automatically cut and transport suitably sized pieces of food to the user's mouth. Each of these is a valid approach to a similar task, yet yield vastly different results. The dividing questions in the framework allow the design problem to be re-framed through multiple lenses, resulting in a diverse range of possible prostheses.

Four task-specific terminal devices were developed as illustrative examples of the four high-level branches of the taxonomy, and in all cases outperformed the anthropomorphic control prosthesis in terms of task performance, compensatory motion, and task load. The terminal devices allowed participants to complete timed tasks—the screwing, stacking checkers, and cutting tasks—in a fraction of the time of the humanoid group, and precision tasks — the flicking and cutting tasks – with a higher accuracy than the humanoid group, contributing to significant reductions in mental demand, physical demand, and frustration. These benefits translated from participants without to participants with upper limb difference, but special attention must be paid to task load to foster a sense of achievement and minimise frustration, and overexertion should be avoided wherever possible. Initial results for psychological embodiment were encouraging, however a dedicated study will be required to extract meaningful conclusions as to the effect of non-humanoid prostheses on embodiment and ownership. Practically, tasks such as cutting and screwing go from being impractical with a conventional prosthesis

to within a user’s capabilities, offering hope that functional non-humanoid prostheses could aid users in returning to work, particularly in physically-skilled jobs. In terms of accuracy-based metrics, the flicking and cutting devices outperformed the anthropomorphic hand consistently. Overall, these results are encouraging, given the pressing need for improved prosthesis functionality [Biddiss et al. 2009; Espinosa and Nathan-Roberts 2019] and the long-term health complications that arise from excessive reliance on compensatory motion to operate a prosthesis [Ephraim et al. 2005; Hanley et al. 2009; Østlie et al. 2011c]. Furthermore, the flicking device shines a light on a much overlooked area of prosthetic device design: social tasks. With lower reported life satisfaction [Østlie et al. 2011b] and social functioning [Johansen et al. 2016] in adults with ULD, socially-designed prostheses could play a large role in improving the lives of this patient population.

A grasp-specific hybrid body-powered/myoelectric prosthesis, the ‘Hydra Hand’, was developed to address shortfalls in myoelectric and body-powered prosthetic technology, and make advanced prosthetic hands accessible to a wider audience of potential users. Mechanical testing of the hand of the prosthesis demonstrated that the mode-switching and finger-locking features present expand the range of possible grasps to a user to include power, cylindrical, and precision grasps. The underactuated nature of the fingers when in power and cylindrical grasping modes allows form closure to be achieved on a range of objects, reducing the force required from the body-powered user input. Work incorporating myoelectric wrist control is ongoing, with results expected after the completion of the PhD.

It is anticipated that the work presented in this chapter could lead to a change in the way that prostheses are approached and designed, leading to functional prostheses that blur the line between human and machine, empowering users to perform actions that are physically and socially meaningful. Due to limitations in contemporary prostheses, straightforward devices that provide such a substantial boost in functionality, along with improvements in usability and long-term comfort, are not only a viable option for adults with upper limb differences; they are a favourable one. This work opens the door to a host of exciting and impactful future research, from the design of new functional and hybrid prostheses to psychological studies exploring the embodiment of non-humanoid prostheses. An open question remains regarding the mechanical implementation of such prostheses. For the functional prostheses in this chapter, the OLYMPIC hand’s modular design [Liow et al. 2020] was leveraged, however the practicality of exchanging individual fingers and switching myoelectric controllers is scenario-dependent. It may be the case that end effectors could be grouped by scenario, such as a ‘kitchen hand’ to perform a set of common cooking tasks such as chopping and stirring. Furthermore, the functional devices developed in this study are all single DOF mechanisms, and higher DOF devices could be developed to perform more complex actions, such as planar writing motion. To encourage further research and development in this area, the design files of the OLYMPIC hand and each functional terminal device, as well as template terminal device adaptors are all open source, available at <https://sites.google.com/view/non-human-hands>. The grasp-specific Hydra prosthe-

sis utilised a body-powered input for grasping and a myoelectric input for wrist rotation, however the possible combinations of execution modes is vast, and functional hybrid upper limb prosthetic devices are an encouraging avenue for future research.

5.8 Conclusions

In this chapter, non-humanoid prosthetic hands were investigated as a viable alternative to conventional anthropomorphic prosthetic hands. The design of upper limb prostheses was investigated via a structured taxonomy, which led to the creation of four task-specific and one grasp-specific prosthetic devices. The task-specific devices exposed new areas of design space, acting as illustrative examples of task-specific electromechanical prostheses that produced hand motion, tool motion, hand function, and tool function. The grasp-specific prosthesis utilised a novel locking mechanism to expand the range of body-powered grasps available to a user, while having a myoelectric input as an option to produce wrist rotation.

All devices offered considerable benefits to their targeted users, with functional devices in particular showing dramatic improvements in terms of task performance, compensatory motion, and task load versus a humanoid prosthesis, and the task-specific device demonstrating a greater range of possible grasps than conventional split-hook body-powered prostheses. Most importantly, the user requirements to operate each prosthetic device were greatly reduced compared to those seen in previous chapters; each functional device required a single myoelectric input, and the Hydra prosthesis is suitable for users who are unable to produce usable myoelectric control signals as a standard body-powered prosthesis, and a single myoelectric input enabling secondary wrist rotation to be achieved.

The results presented in this chapter clearly show that benefits in functionality, comfort, and ease-of-use can be obtained via the adoption of a non-humanoid design ideology. The devices presented were mechanically simple and effective, and required far less complex controllers than those used to achieve advanced discrete control and continuous control. It is hoped that this will lead to the wider adoption of such designs, both in research and in industry.

Chapter 6

Conclusions

This thesis presents a multifaceted, user-centred approach to improving myoelectric prosthetic hand control. The approach taken across all work presented in this thesis is that a myoelectric prosthetic hand is a human-in-the-loop system; user training and end-effector design are as important as the myoelectric controller itself. Each chapter addressed key challenges surrounding existing approaches to myoelectric prosthetic hand control, specifically overcoming poor user training in the time building up to prosthetic hand use, the limited data requirements and computational capabilities of myoelectric hands, the poor precision and psychological embodiment of open-loop discretely controlled prosthetic hands, and the poor functionality of humanoid prosthetic hands. Furthermore, the evaluation techniques utilised in this thesis — task performance, task load, psychological embodiment, and compensatory motion — were used together to provide a more complete picture of the complex physical and psychological characteristics of prosthetic hand control than any one evaluation metric by itself. These evaluation techniques, regular input from The Alex Lewis Trust, and insights gained from informal participant feedback during each study helped to guide the research presented in each chapter to be as meaningful as possible and maximise potential impact.

6.1 Summary of Main Contributions

In Chapter 2, a robot-enhanced virtual reality platform was presented that rendered force feedback from a realistically simulated prosthetic hand such that the user could feel forces associated with wearing a prosthesis, such as prosthesis weight and projected contact forces. Existing training platforms were either two-dimensional games or animation-based virtual reality systems. The platform was evaluated with participants without upper limb difference representing novice prosthetic hand users, who performed pick and place tasks via the Box and Blocks Test [Trombly and Scott 1983] and with items from the YCB Object and Model Set [Calli et al. 2017], followed by evaluation of task load via the NASA Task Load Index questionnaire [Hart and Staveland 1988]. Results identified the dangers of virtual training without feedback negatively impacting performance, as well as the bene-

fits of robot-enhanced virtual reality training in more adequately preparing novice users for real-life prosthesis use.

In Chapter 3, two discrete myoelectric control algorithms were presented, the first being a deep learning-based controller that was trained directly on the prosthesis, and the second a novel minimal-data discrete myoelectric controller. In literature, the majority of research effort over recent decades has been spent developing more complex discrete myoelectric controllers, often at the cost of larger and larger calibration data requirements from their users. The two developed controllers performed comparably to those seen in literature, using a smaller amount of user data and being suitable for implementation on a prosthetic hand, most notably the latter controller, which required a fraction of the user data of comparable deep learning-based controllers. The minimal-data controller was physically evaluated using the Jebsen-Taylor Hand Function Test [Jebsen et al. 1969], quantifying the ability of participants to perform activities of daily living, which was demonstrated to translate to end-users via testing with a participant with upper limb difference.

In Chapter 4, a closed-loop continuous controller is presented and thoroughly evaluated physically and psychologically by participants with and without upper limb difference. To achieve this, a multi-modal proprioceptive sensory feedback armband was developed, and its haptic properties were evaluated. This was combined with an extended version of the minimal-data discrete controller presented in Chapter 3 that was developed to regress activation proportions of multiple degrees of freedom of actuation of a prosthetic hand. Together, these formed a closed-loop continuous controller, which was evaluated against closed-loop discrete control, open-loop continuous control, and open-loop discrete control on a range of isolated tasks, contextual activities of daily living, task load and psychological embodiment questionnaires, and post-study interviews (for participants with upper limb difference). Results demonstrated the benefits of closed-loop continuous control when performing isolated and precision tasks, and also areas where discrete control is most suitable for use, such as on manual tasks. Closed-loop continuous control was found to improve the rate of participant psychological embodiment, however the responses of participants with upper limb difference were much more sensitive to external and personal factors than those without upper limb difference, with detailed reasoning found in post-study interviews.

Finally, in Chapter 5, the design of the myoelectrically controlled prosthesis was examined, identifying key categories of upper limb prosthesis and regions of design space that are currently unoccupied by myoelectric prosthetic hands. Specifically, existing electromechanical prosthetic hands have been limited to imitating human hand motion (via gesturing and multi-articulation) and human hand function (via grasping), while fictional electromechanical prosthetic hands have displayed a wide range of task-specific, tool-imitating features. To occupy these regions, four task-specific terminal devices and one grasp-specific hybrid myoelectric-body-powered prosthetic hand were presented. Via a control group study with participants without upper limb difference, the four task-specific devices were shown

to outperform a conventional prosthetic hand dramatically, in terms of task performance, compensatory body motion, and task load. These results were shown to translate to participants with upper limb difference, and preliminary psychological embodiment results were encouraging. The mechanical design of the grasp-specific hybrid prosthetic hand was presented and evaluated using the YCB Gripper Assessment Benchmark [Calli et al. 2015] and the Soft Object Gripper Benchmark [Clark et al. 2023], where the hand was shown to be able to grasp a range of objects in spherical, cylindrical, and precision grips.

6.2 Strengths

A key strength of this thesis lies in its multifaceted approach. Only through considering the myoelectric controller as part of a larger, human-in-the-loop system could key subsystems and areas of improvement be identified. Furthermore, through multifaceted evaluation, a more complete picture of the effects of each development presented in this thesis could be obtained, offering greater insights into their potential long term benefits and drawbacks than any one isolated evaluation method. This multifaceted approach is a key novelty of the thesis overall, and it is hoped that the work presented in this thesis will encourage other researchers in the field of upper limb prosthetics to adopt similar approaches.

A further strength of this thesis is that it diverges from established norms in the field of upper limb prosthetics. In particular, key current research trends are challenged, such as virtual reality as a training tool, data-hungry discrete and continuous control, and anthropomorphic prosthetic hand design. Challenging these norms and diverging from convention was only possible due to regular, honest input, primarily from participants with upper limb difference, but also from charity organisations and industry partners. Perhaps most importantly, nearly all of the participants with upper limb difference that were recruited to the studies presented in this thesis had previously rejected myoelectric prosthetic hands. Candid discussions, not only about their thoughts on each study, but also about their personal experiences with prosthetic devices of all kinds led to the identification of many unexpected research directions.

6.3 Limitations

The research presented in this thesis is not without its limitations. One of the most important and challenging limitations to overcome — and indeed one that is shared by almost every study in the field of upper limb prosthetics — is the relatively small number of participants with upper limb difference recruited to each study. 10 participants with upper limb difference participated in the study presented in Chapter 4, in one of the largest studies that has taken place to evaluate a new myoelectric control method. However, as discussed, participant results were incredibly diverse due to heterogeneity within the population of participants with upper limb difference, with no common trends observed

across all participants, particularly in terms of psychological results. Because of this, group statistics and quantitative evidence that the contributions presented in this thesis will translate to the wider population of potential myoelectric prosthetic hand users cannot be computed with any certainty. Given the difficulties in recruiting participants, it is likely that this will remain a limitation of future studies unless a concerted effort is made across research groups to engage with a wider population of potential participants.

Another key limitation of the work presented in this thesis is the short-form, controlled-environment nature of each study. Even the longest study presented in Chapter 4, which took place over three 2.5-hour sessions (or an equivalent single session) in a desk-based setting, is a far cry from capturing the long term effects of developments to myoelectric prosthetic hand control that arise from use in daily life. This is particularly important when assessing psychological phenomena such as embodiment and ownership and understanding the effects of physical performance-related factors such as learning, which develop over markedly longer time frames than a single session and in environments that are specific to each participant. At-home, longitudinal studies are required to understand in greater depth how myoelectric prosthetic hand control research translates to daily use.

Finally, although a large effort was made to assess the physical and psychological effects of myoelectric prosthetic hand control via multifaceted approaches, it is clear that further assessment techniques are required to capture a complete picture of the relationship between a user and prosthesis. This was most apparent when inspecting psychological embodiment results, which were subject to dramatic fluctuations that did not necessarily correlate to the physical performance and task load results captured concurrently. Complementary qualitative methods such as post-study interviews produced further insights into these events, but lacked the ability to quantify any effects numerically.

6.4 Future Work

In response to this thesis, it is primarily hoped that, both in academia and industry, more targeted efforts will be made to improve myoelectric control from a practical, human-centred approach, with multifaceted evaluation techniques being utilised to inform and refine these improvements. Beyond this, it is also hoped that this thesis will encourage the involvement of end-users in all aspects of research, from conception through to experimentation. Each chapter in this thesis has highlighted promising, exciting avenues for future research and potential applications, some of which are listed below.

- **Personalised and assistive robot-enhanced virtual reality training:** The robot-enhanced virtual reality platform presented in Chapter 2 can be used for individualised training by presenting users with personalised training scenarios that reflect activities of daily living that are relevant to the patient, and can be adjusted freely to increase or decrease difficulty. Furthermore,

the robot-enhanced aspect of the training platform can be assistive; rather than only rendering force feedback from the simulation, the robot arm can negate the weight of the prosthetic arm. This assistance can then be reduced as the user builds strength during their pre-prosthetic training.

- **User personalisation of prosthetic technology in virtual reality:** The terminal devices presented in Chapter 5 represent only a fraction of the possible upper limb prosthetic end effectors. Physically manufacturing each possible device for end-user testing is infeasible, so the virtual reality platform presented in Chapter 2 is an appealing alternative to physical testing. New designs can be rapidly trialled without using physical resources and without delay.
- **Computational acceleration of Wasserstein distance-based controllers:** The controllers presented in Chapters 3 and 4 rely on kernel density estimation with a custom kernel, as well as the computation of the Wasserstein distance at each control step. Both of these are computationally intensive, and were possible to implement on the prosthetic hand due to the onboard Nvidia Jetson Nano. However, to allow these controllers to be applied to a wider range of prosthetic hands, a dedicated effort should be made to simplify and accelerate their computation.
- **Sensory feedback from non-humanoid upper limb prostheses:** It was shown in Chapter 4 that sensory feedback can improve task performance and psychological embodiment of a prosthetic hand. However, when applying this to the non-humanoid upper limb prostheses developed in Chapter 5, this is non-trivial, given the lack of a natural correspondence between a non-humanoid device and the feedback mechanisms used to render sensory feedback from the device to its user.
- **Psychological embodiment of non-humanoid upper limb prostheses:** Despite showing great improvements in terms of task performance, comfort, and ease of use, psychological embodiment results for each non-humanoid prosthetic device presented in Chapter 5 were inconclusive. The acceptance of a prosthesis by its user is important in order to avoid rejection, however, this phenomenon is one that evolves over longer use periods than a single study session. In order to truly examine how users embody non-humanoid prostheses, at-home, longitudinal studies must be performed where participants incorporate non-humanoid prosthesis use into their daily life.

Bibliography

- Abd, Moaed A., Joseph Ingicco, Douglas T. Hutchinson, Emmanuelle Tognoli, and Erik D. Engeberg (Feb. 2022). “Multichannel haptic feedback unlocks prosthetic hand dexterity”. In: *Scientific Reports 2022 12:1* 12.1, pp. 1–17. (Cited on page 57.)
- Alexander, Peter G., Karen L. Clark, and Rocky S. Tuan (Sept. 2016). “Prenatal exposure to environmental factors and congenital limb defects”. In: *Birth Defects Research Part C: Embryo Today: Reviews* 108.3, pp. 243–273. (Cited on page 3.)
- Alkan, Ahmet and Mücahid Günay (2012). “Identification of EMG signals using discriminant analysis and SVM classifier”. In: *Expert systems with Applications* 39.1, pp. 44–47. (Cited on page 34.)
- Almström, C., P. Herberts, and L. Körner (June 1981). “Experience with swedish multifunctional prosthetic hands controlled by pattern recognition of multiple myoelectric signals”. In: *International Orthopaedics* 5.1, pp. 15–21. (Cited on pages 8, 34, 55.)
- Ameri, Ali, Mohammad Ali Akhaee, Erik Scheme, and Kevin Englehart (Apr. 2019). “Regression convolutional neural network for improved simultaneous EMG control”. In: *Journal of Neural Engineering* 16.3, p. 036015. (Cited on page 9.)
- Antfolk, Christian, Christian Cipriani, Maria Chiara Carrozza, Christian Balkenius, Anders Björkman, Göran Lundborg, Birgitta Rosén, and Fredrik Sebelius (May 2013). “Transfer of tactile input from an artificial hand to the forearm: experiments in amputees and able-bodied volunteers”. In: *Disability and Rehabilitation: Assistive Technology* 8.3, pp. 249–254. (Cited on page 57.)
- Antfolk, Christian, Marco D’alonzo, Birgitta Rosén, Göran Lundborg, Fredrik Sebelius, and Christian Cipriani (Jan. 2014). “Sensory feedback in upper limb prosthetics”. In: *Expert Review of Medical Devices* 10.1, pp. 45–54. (Cited on page 55.)
- Arabian, Adam, Dante Varotsis, Caitlin McDonnell, and Elinor Meeks (2016). “Global social acceptance of prosthetic devices”. In: *GHTC 2016 - IEEE Global Humanitarian Technology Conference: Technology for the Benefit of Humanity, Conference Proceedings*, pp. 563–568. (Cited on page 84.)
- Atkins, Diane J., Denise C. Y. Heard, and William H. Donovan (1996). “Epidemiologic Overview of Individuals with Upper-Limb Loss and Their Reported Research Priorities”. In: *Journal of Prosthetics and Orthotics* 8.1, pp. 2–11. (Cited on pages 1, 2, 82, 83.)

- Atzori, Manfredo, Matteo Cognolato, and Henning Müller (2016). “Deep learning with convolutional neural networks applied to electromyography data: A resource for the classification of movements for prosthetic hands”. In: *Frontiers in neurorobotics* 10, p. 9. (Cited on page 35.)
- Backus, Spencer B. and Aaron M. Dollar (Apr. 2018). “A prismatic-revolute-revolute joint hand for grasping from unmanned aerial vehicles and other minimally Constrained Vehicles”. In: *Journal of Mechanisms and Robotics* 10.2. (Cited on page 107.)
- Bai, Guochao, Xianwen Kong, and James Millar Ritchie (June 2017). “Kinematic analysis and dimensional synthesis of a meso-gripper”. In: *Journal of Mechanisms and Robotics* 9.3. (Cited on page 85.)
- Battye, C. K., A. Nightingale, and J. Whillis (Aug. 1955). “The use of myo-electric currents in the operation of prostheses.” In: *The Journal of bone and joint surgery. British volume* 37 B.3, pp. 506–510. (Cited on pages 2, 5, 82.)
- Bekrater-Bodmann, Robin (Aug. 2020). “Perceptual correlates of successful body–prosthesis interaction in lower limb amputees: psychometric characterisation and development of the Prosthesis Embodiment Scale”. In: *Scientific Reports 2020 10:1* 10.1, pp. 1–13. (Cited on pages 57, 65, 144.)
- Belter, Joseph T., Jacob L. Segil, Aaron M. Dollar, and Richard F. Weir (2013). “Mechanical design and performance specifications of anthropomorphic prosthetic hands: a review”. In: *Journal of Rehabilitation Research and Development* 50.5, pp. 599–618. (Cited on page 55.)
- Benz, Heather, Jia Yao, Laura Rose, Okan Olgac, Karen Kreutz, Anindita Saha, and Eugene Civillico (Aug. 2016). “Upper extremity prosthesis user perspectives on unmet needs and innovative technology”. In: *International Conference of the IEEE Engineering in Medicine and Biology Society*. Vol. 2016. IEEE, pp. 287–290. (Cited on page 57.)
- Berkovic, Alexandre, Colin Laganier, Digby Chappell, Thrishantha Nanayakkara, Petar Kormushev, Fernando Bello, and Nicolas Rojas (May 2022). “A Multi-Modal Haptic Armband for Finger-Level Sensory Feedback from a Prosthetic Hand”. In: *Haptics: Science, Technology, Applications, EuroHaptics*. Hamburg: Springer, pp. 138–146. (Cited on pages 15, 54.)
- Betthausen, Joseph L., John T. Krall, Shain G. Bannowsky, Gyorgy Levay, Rahul R. Kaliki, Matthew S. Fifer, and Nitish V. Thakor (June 2020). “Stable responsive emg sequence prediction and adaptive reinforcement with temporal convolutional networks”. In: *IEEE Transactions on Biomedical Engineering* 67.6, pp. 1707–1717. (Cited on page 9.)
- Bianchi, Bruno, Andy Heyward, and Jean Chalopin (1983). *Inspector Gadget*. (Cited on page 88.)
- Biddiss, Elaine, Dorcas Beaton, and Tom Chau (2009). “Consumer design priorities for upper limb prosthetics”. In: *Disability and Rehabilitation: Assistive Technology* 2.6, pp. 346–357. (Cited on pages 82, 83, 84, 113.)

- Biddiss, Elaine and Tom Chau (Sept. 2007a). “Upper limb prosthesis use and abandonment: A survey of the last 25 years”. In: *Prosthetics and Orthotics International* 31.3, pp. 236–257. (Cited on page 2.)
- (Dec. 2007b). “Upper-limb prosthetics: Critical factors in device abandonment”. In: *American Journal of Physical Medicine and Rehabilitation* 86.12, pp. 977–987. (Cited on pages 2, 79.)
- Biddiss, Elaine, Patricia McKeever, Sally Lindsay, and Tom Chau (June 2011). “Implications of prosthesis funding structures on the use of prostheses: Experiences of individuals with upper limb absence”. In: *Prosthetics and Orthotics International* 35.2, pp. 215–224. (Cited on page 4.)
- Blackrock Special Hospital (1921). *Hammer Hand*. Dublin. (Cited on page 4.)
- Blue Godfrey, Sasha, Matteo Rossi, Cristina Piazza, Manuel Giuseppe Catalano, Matteo Bianchi, Giorgio Grioli, Kristin D Zhao, and Antonio Bicchi (2017). “SoftHand at the CYBATHLON: a user’s experience”. In: *Journal of NeuroEngineering and Rehabilitation* 14, p. 124. (Cited on page 55.)
- Bottomley, A. H. (Aug. 1965). “Myo-Electric Control of Powered Prostheses”. In: *The Journal of bone and joint surgery. British volume* 47.3, pp. 411–415. (Cited on page 6.)
- Botvinick, M. and J. Cohen (Feb. 1998). “Rubber hands ‘feel’ touch that eyes see”. In: *Nature* 1998 391:6669 391.6669, pp. 756–756. (Cited on page 65.)
- Bouwsema, Hanneke, Corry K. Van Der Sluis, and Raoul M. Bongers (May 2014). “Effect of Feedback during Virtual Training of Grip Force Control with a Myoelectric Prosthesis”. In: *PLOS ONE* 9.5, e98301. (Cited on pages 20, 40.)
- Boxtel, A. van, A.J.W. Boelhouwer, and A.R. Bos (Nov. 1998). “Optimal EMG signal bandwidth and interelectrode distance for the recording of acoustic, electrocutaneous, and photic blink reflexes”. In: *Psychophysiology* 35.6, pp. 690–697. (Cited on page 6.)
- Brinton, Mark R., Elliott Barcikowski, Tyler Davis, Michael Paskett, Jacob A. George, and Gregory A. Clark (Sept. 2020). “Portable Take-Home System Enables Proportional Control and High-Resolution Data Logging With a Multi-Degree-of-Freedom Bionic Arm”. In: *Frontiers in Robotics and AI* 7, p. 133. (Cited on pages 2, 56.)
- Burke, J. W., M. D.J. McNeill, D. K. Charles, P. J. Morrow, J. H. Crosbie, and S. M. McDonough (2009). “Serious games for upper limb rehabilitation following stroke”. In: *Proceedings of the 2009 Conference in Games and Virtual Worlds for Serious Applications, VS-GAMES 2009*, pp. 103–110. (Cited on page 20.)
- Burton, Tim (1990). *Edward Scissorhands*. (Cited on page 89.)
- Calli, Berk, Arjun Singh, James Bruce, Aaron Walsman, Kurt Konolige, Siddhartha Srinivasa, Pieter Abbeel, and Aaron M Dollar (Mar. 2017). “Yale-CMU-Berkeley dataset for robotic manipulation research”. In: *The International Journal of Robotics Research* 36.3, pp. 261–268. (Cited on pages 19, 28, 115.)

- Calli, Berk, Aaron Walsman, Arjun Singh, Siddhartha Srinivasa, Pieter Abbeel, and Aaron M. Dollar (Sept. 2015). “Benchmarking in Manipulation Research: Using the Yale-CMU-Berkeley Object and Model Set”. In: *IEEE Robotics and Automation Magazine* 22.3, pp. 36–52. (Cited on pages 9, 102, 117.)
- Capsi-Morales Id, Patricia, Cristina Piazza Id, Lis Sjoberg Id, Manuel G Catalano, Giorgio Grioli, Antonio Bicchi, and Liselotte M Hermanssonid (Aug. 2023). “Functional assessment of current upper limb prostheses: An integrated clinical and technological perspective”. In: *PLOS ONE* 18.8. Ed. by Andrea Tigrini, e0289978. (Cited on page 97.)
- Caserta, Giulia, Nicolò Boccardo, Marco Freddolini, Giacinto Barresi, Andrea Marinelli, Michele Canepa, Samuel Stedman, Lorenzo Lombardi, Matteo Laffranchi, Emanuele Gruppioni, and Lorenzo De Michieli (Dec. 2022). “Benefits of the Cybathlon 2020 experience for a prosthetic hand user: a case study on the Hannes system”. In: *Journal of NeuroEngineering and Rehabilitation* 19.1, pp. 1–15. (Cited on pages 12, 97.)
- Cha, Hyeongdo, Sion An, Seoyoung Choi, Seungun Yang, Sanghyun Park, and Sukho Park (2022). “Study on Intention Recognition and Sensory Feedback: Control of Robotic Prosthetic Hand through EMG Classification and Proprioceptive Feedback using Rule-based Haptic Device”. In: *IEEE Transactions on Haptics* 15.3, pp. 560–571. (Cited on page 57.)
- Chappell, Digby, Fernando Bello, Petar Kormushev, and Nicolas Rojas (Sept. 2023). “The Hydra Hand: A Mode-Switching Underactuated Gripper with Precision and Power Grasping Modes”. In: *IEEE Robotics and Automation Letters* 8.11, pp. 7599–7606. (Cited on pages 15, 82.)
- Chappell, Digby, Barry Mulvey, Shehara Perera, Fernando Bello, Petar Kormushev, and Nicolas Rojas (2024a). “Beyond Humanoid Prosthetic Hands: Modular Terminal Devices That Improve User Performance”. In: *IEEE Transactions on Medical Robotics and Bionics (Under Review)*. (Cited on pages 16, 82.)
- Chappell, Digby, Honn Wee Son, Angus B. Clark, Zeyu Yang, Fernando Bello, Petar Kormushev, and Nicolas Rojas (Apr. 2022a). “Virtual Reality Pre-Prosthetic Hand Training with Physics Simulation and Robotic Force Interaction”. In: *IEEE Robotics and Automation Letters* 7.2, pp. 4550–4557. (Cited on pages 15, 17, 63.)
- Chappell, Digby, Zeyu Yang, Angus B. Clark, Alexandre Berkovic, Colin Laganier, Weston Baxter, Fernando Bello, Petar Kormushev, and Nicolas Rojas (2024b). “Combining multimodal feedback with continuous control improves performance and psychological embodiment in prosthetic hand users”. In: *Scientific Reports (Under Review)*. (Cited on pages 15, 54.)
- Chappell, Digby, Zeyu Yang, Honn Wee Son, Fernando Bello, Petar Kormushev, and Nicolas Rojas (July 2022b). “Towards Instant Calibration in Myoelectric Prosthetic Hands: A Highly Data-Efficient Controller Based on the Wasserstein Distance”. In: *IEEE International Conference on Rehabilitation Robotics (ICORR)*. Rotterdam: IEEE, pp. 1–6. (Cited on pages 15, 33.)

- Cheesborough, Jennifer E., Lauren H. Smith, Todd A. Kuiken, and Gregory A. Dumanian (2015). “Targeted Muscle Reinnervation and Advanced Prosthetic Arms”. In: *Seminars in Plastic Surgery* 29.1, p. 62. (Cited on page 2.)
- Cheng, Kodi Y., Craig S. Chapman, and Jacqueline S. Hebert (2022). “Spatiotemporal Coupling of Hand and Eye Movements When Using a Myoelectric Prosthetic Hand”. In: *IEEE International Conference on Rehabilitation Robotics* 2022-July. (Cited on page 12.)
- Cho, Younggeol, Yeongseok Lee, Pyungkang Kim, Seokhwan Jeong, and Kyung Soo Kim (Apr. 2022). “The MSC Prosthetic Hand: Rapid, Powerful, and Intuitive”. In: *IEEE Robotics and Automation Letters* 7.2, pp. 3170–3177. (Cited on pages 55, 78, 82, 83, 86.)
- Chowdhury, Rubana H., Mamun B.I. Reaz, Mohd Alauddin Bin Mohd Ali, Ashrif A.A. Bakar, K. Chellappan, and T. G. Chang (Sept. 2013). “Surface Electromyography Signal Processing and Classification Techniques”. In: *Sensors 2013, Vol. 13, Pages 12431-12466* 13.9, pp. 12431–12466. (Cited on pages 8, 57, 59.)
- Ciocarlie, Matei, Fernando Mier Hicks, Robert Holmberg, Jeffrey Hawke, Michael Schlicht, Jeff Gee, Scott Stanford, and Ryan Bahadur (Feb. 2014). “The Velo gripper: A versatile single-actuator design for enveloping, parallel and fingertip grasps”. In: *The International Journal of Robotics Research* 33.5, pp. 753–767. (Cited on pages 85, 101.)
- Clark, Angus B., Luke Cramphorn-Neal, Michal Rachowiecki, and Austin Gregg-Smith (2023). “Household Clothing Set and Benchmarks for Characterising End-Effector Cloth Manipulation”. In: *IEEE International Conference on Robotics and Automation (ICRA)*. (Cited on pages 9, 102, 117.)
- Clemente, Francesco, Marco D’Alonzo, Marco Controzzi, Benoni B. Edin, and Christian Cipriani (Dec. 2016). “Non-Invasive, Temporally Discrete Feedback of Object Contact and Release Improves Grasp Control of Closed-Loop Myoelectric Transradial Prostheses”. In: *IEEE Transactions on Neural Systems and Rehabilitation Engineering* 24.12, pp. 1314–1322. (Cited on page 57.)
- Clemente, Francesco, Giacomo Valle, Marco Controzzi, Ivo Strauss, Francesco Iberite, Thomas Stieglitz, Giuseppe Granata, Paolo M. Rossini, Francesco Petrini, Silvestro Micera, and Christian Cipriani (Feb. 2019). “Intraneural sensory feedback restores grip force control and motor coordination while using a prosthetic hand”. In: *Journal of Neural Engineering* 16.2, p. 026034. (Cited on pages 2, 56.)
- Côté-Allard, U, C L Fall, A Drouin, A Campeau-Lecours, C Gosselin, K Glette, F Laviolette, and B Gosselin (2019). “Deep Learning for Electromyographic Hand Gesture Signal Classification Using Transfer Learning”. In: *IEEE Transactions on Neural Systems and Rehabilitation Engineering* 27.4, pp. 760–771. (Cited on pages 35, 50.)
- Czeizel, A. E., I. Kodaj, and W. Lenz (June 1994). “Smoking during pregnancy and congenital limb deficiency”. In: *BMJ* 308.6942, pp. 1473–1476. (Cited on page 3.)

- D’Anna, Edoardo, Giacomo Valle, Alberto Mazzoni, Ivo Strauss, Francesco Iberite, J  r  my Patton, Francesco M. Petrini, Stanisa Raspopovic, Giuseppe Granata, Riccardo Di Iorio, Marco Controzzi, Christian Cipriani, Thomas Stieglitz, Paolo M. Rossini, and Silvestro Micera (Feb. 2019). “A closed-loop hand prosthesis with simultaneous intraneural tactile and position feedback”. In: *Science Robotics* 4.27. (Cited on pages 2, 56.)
- Dakpa, R. and H. Heger (July 1997). “Prosthetic management and training of adult upper limb amputees”. In: *Current Orthopaedics* 11.3, pp. 193–202. (Cited on page 20.)
- Datta, Dipak, Kanther Selvarajah, and Nicola Davey (Mar. 2004). “Functional outcome of patients with proximal upper limb deficiency–acquired and congenital”. In: *Clinical Rehabilitation* 18.2, pp. 172–177. (Cited on page 83.)
- Dawson, Michael R., Jason P. Carey, and Farbod Fahimi (Sept. 2014). “Myoelectric training systems”. In: *Expert Review of Medical Devices* 8.5, pp. 581–589. (Cited on page 20.)
- De Arco, L, O Ramos, M Munera, M Moazen, Helge Wurdemann, and CA Cifuentes (2022). “The Pr-Hand: Functional Assessment of an Underactuated Soft-Robotic Prosthetic Hand”. In: *Proceedings of the 9th IEEE RAS/EMBS International Conference on Biomedical Robotics & Biomechanics*, pp. 1–6. (Cited on pages 82, 83.)
- Demir, Fatih, Varun Bajaj, Melih Ince, Sachin Taran, and Abdulkadir Sengur (June 2019). “Surface EMG signals and deep transfer learning-based physical action classification”. In: *Neural Computing and Applications* 31. (Cited on page 35.)
- Dhawan, Ananya S., Biswarup Mukherjee, Shriniwas Patwardhan, Nima Akhlaghi, Guoqing Diao, Gyorgy Levay, Rahsaan Holley, Wilsaan M. Joiner, Michelle Harris-Love, and Siddhartha Sikdar (July 2019a). “Proprioceptive Sonomyographic Control: A novel method for intuitive and proportional control of multiple degrees-of-freedom for individuals with upper extremity limb loss”. In: *Scientific Reports* 2019 9:1 9.1, pp. 1–15. (Cited on page 5.)
- Dhawan, Darpan, Michael Barlow, and Erandi Lakshika (Aug. 2019b). “Prosthetic Rehabilitation Training in Virtual Reality”. In: *2019 IEEE 7th International Conference on Serious Games and Applications for Health, SeGAH 2019*. (Cited on pages 18, 20, 21.)
- Dollar, Aaron M. and Robert D. Howe (2007). “The SDM hand as a prosthetic terminal device: A feasibility study”. In: *2007 IEEE 10th International Conference on Rehabilitation Robotics, ICORR’07*, pp. 978–983. (Cited on page 86.)
- Dorrance, David W. (Feb. 1912). *Artificial Hand*. (Cited on page 5.)
- Dyson, Matthew, Jessica Barnes, and Kianoush Nazarpour (July 2018). “Myoelectric control with abstract decoders”. In: *Journal of Neural Engineering* 15.5, p. 056003. (Cited on pages 57, 83.)
- Dyson, Matthew, Sigrid Dupan, Hannah Jones, and Kianoush Nazarpour (July 2020). “Learning, Generalization, and Scalability of Abstract Myoelectric Control”. In: *IEEE Transactions on Neural Systems and Rehabilitation Engineering* 28.7, pp. 1539–1547. (Cited on pages 57, 83.)

- Engdahl, Susannah M., Christina Lee, and Deanna H. Gates (July 2022). “A comparison of compensatory movements between body-powered and myoelectric prosthesis users during activities of daily living”. In: *Clinical Biomechanics* 97, p. 105713. (Cited on page 5.)
- Engdahl, Susannah M., Sean K. Meehan, and Deanna H. Gates (Sept. 2020). “Differential experiences of embodiment between body-powered and myoelectric prosthesis users”. In: *Scientific Reports* 2020 10:1 10.1, pp. 1–10. (Cited on page 78.)
- Englehart, Kevin and Bernard Hudgins (2003). “A robust, real-time control scheme for multifunction myoelectric control”. In: *IEEE transactions on biomedical engineering* 50.7, pp. 848–854. (Cited on page 34.)
- Ephraim, Patti L., Stephen T. Wegener, Ellen J. MacKenzie, Timothy R. Dillingham, and Liliana E. Pezzin (Oct. 2005). “Phantom Pain, Residual Limb Pain, and Back Pain in Amputees: Results of a National Survey”. In: *Archives of Physical Medicine and Rehabilitation* 86.10, pp. 1910–1919. (Cited on pages 83, 113.)
- Espinosa, Monica and Dan Nathan-Roberts (Nov. 2019). “Understanding Prosthetic Abandonment”. In: *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* 63.1, pp. 1644–1648. (Cited on pages 2, 82, 113.)
- Farina, D, N Jiang, H Rehbaum, A Holobar, B Graimann, H Dietl, and O C Aszmann (2014). “The Extraction of Neural Information from the Surface EMG for the Control of Upper-Limb Prostheses: Emerging Avenues and Challenges”. In: *IEEE Transactions on Neural Systems and Rehabilitation Engineering* 22.4, pp. 797–809. (Cited on pages 34, 41.)
- Featherstone, Roy (2008). *Rigid Body Dynamics Algorithms*. Springer US. (Cited on page 25.)
- Feix, Thomas, Javier Romero, Heinz Bodo Schmiedmayer, Aaron M. Dollar, and Danica Kragic (Feb. 2016). “The GRASP Taxonomy of Human Grasp Types”. In: *IEEE Transactions on Human-Machine Systems* 46.1, pp. 66–77. (Cited on pages 37, 98.)
- Feydy, Jean, Thibault Séjourné, François-Xavier Vialard, Shun-Ichi Amari, Alain Trouvé, and Gabriel Peyré (2019). “Interpolating between Optimal Transport and MMD using Sinkhorn Divergences”. In: *AISTATS*, pp. 2681–2690. (Cited on page 45.)
- Finley, F. R. and R. W. Wirta (Jan. 1967). “Myocoder-computer study of electromyographic patterns.” In: *Archives of Physical Medicine and Rehabilitation* 48.1, pp. 20–24. (Cited on pages 7, 33, 34, 55.)
- Furui, Akira, Shintaro Eto, Kosuke Nakagaki, Kyohei Shimada, Go Nakamura, Akito Masuda, Takaaki Chin, and Toshio Tsuji (2019). “A myoelectric prosthetic hand with muscle synergybased motion determination and impedance modelbased biomimetic control”. In: *Science Robotics* 4.31. (Cited on page 78.)
- Gaine, W. J., C. Smart, and M. Bransby-Zachary (Feb. 1997). “Upper Limb Traumatic Amputees”. In: *Journal of Hand Surgery (European Volume)* 22.1, pp. 73–76. (Cited on pages 1, 2.)

- Gasparic, Filip, Nikola Jorgovanovic, Christian Hofer, Michael F. Russold, Mario Koppe, Darko Stanisic, and Strahinja Dosen (2023). “A Novel Sensory Feedback Approach to Facilitate Both Predictive and Corrective Control of Grasping Force in Myoelectric Prostheses”. In: *IEEE Transactions on Neural Systems and Rehabilitation Engineering* 31, pp. 4492–4503. (Cited on page 10.)
- Geethanjali, Purushothaman (July 2016). *Myoelectric control of prosthetic hands: State-of-the-art review*. (Cited on page 5.)
- George, J. A., D. T. Kluger, T. S. Davis, S. M. Wendelken, E. V. Okorokova, Q. He, C. C. Duncan, D. T. Hutchinson, Z. C. Thumser, D. T. Beckler, P. D. Marasco, S. J. Bensmaia, and G. A. Clark (July 2019). “Biomimetic sensory feedback through peripheral nerve stimulation improves dexterous use of a bionic hand”. In: *Science Robotics* 4.32. (Cited on pages 2, 56, 57.)
- George, Jacob A, Mark R Brinton, Christopher C Duncan, Douglas T Hutchinson, and Gregory A Clark (2018). “Improved training paradigms and motor-decode algorithms: results from intact individuals and a recent transradial amputee with prior complex regional pain syndrome”. In: *2018 40th annual international conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*. IEEE, pp. 3782–3787. (Cited on page 35.)
- Ghazaei, Ghazal, Ali Alameer, Patrick Degenaar, Graham Morgan, and Kianoush Nazarpour (May 2017). “Deep learning-based artificial vision for grasp classification in myoelectric hands”. In: *Journal of Neural Engineering* 14.3, p. 036025. (Cited on page 10.)
- Giele, Henk, Carolien Giele, Carol Bower, and Mark Allison (July 2001). “The incidence and epidemiology of congenital upper limb anomalies: A total population study”. In: *The Journal of Hand Surgery* 26.4, pp. 628–634. (Cited on page 1.)
- Godfrey, Sasha Blue, Kristin D. Zhao, Amanda Theuer, Manuel G. Catalano, Matteo Bianchi, Ryan Breighner, Divya Bhaskaran, Ryan Lennon, Giorgio Grioli, Marco Santello, Antonio Bicchi, and Karen Andrews (Oct. 2018). “The SoftHand Pro: Functional evaluation of a novel, flexible, and robust myoelectric prosthesis”. In: *PLOS ONE* 13.10, e0205653. (Cited on page 86.)
- Gu, Guoying, Ningbin Zhang, Haipeng Xu, Shaoting Lin, Yang Yu, Guohong Chai, Lisen Ge, Houle Yang, Qiwen Shao, Xinjun Sheng, Xiangyang Zhu, and Xuanhe Zhao (Aug. 2021). “A soft neuroprosthetic hand providing simultaneous myoelectric control and tactile feedback”. In: *Nature Biomedical Engineering* 2021 5, pp. 1–10. (Cited on pages 57, 83.)
- Hahne, J M, F Bießmann, N Jiang, H Rehbaum, D Farina, F C Meinecke, K -. Müller, and L C Parra (2014). “Linear and Nonlinear Regression Techniques for Simultaneous and Proportional Myoelectric Control”. In: *IEEE Transactions on Neural Systems and Rehabilitation Engineering* 22.2, pp. 269–279. (Cited on page 8.)
- Hahne, Janne M., Meike A. Schweisfurth, Mario Koppe, and Dario Farina (June 2018). “Simultaneous control of multiple functions of bionic hand prostheses: Performance and robustness in end users”. In: *Science Robotics* 3.19. (Cited on pages 8, 57, 83.)

- Hammond, Frank L., Jonathan Weisz, Andrés A. De La Llera Kurth, Peter K. Allen, and Robert D. Howe (2012). “Towards a design optimization method for reducing the mechanical complexity of underactuated robotic hands”. In: *IEEE International Conference on Robotics and Automation*, pp. 2843–2850. (Cited on page 84.)
- Hanley, M. A., D. M. Ehde, M. Jensen, J. Czerniecki, D. G. Smith, and L. R. Robinson (Aug. 2009). “Chronic Pain Associated with Upper-Limb Loss”. In: *American Journal of Physical Medicine & Rehabilitation* 88.9, p. 742. (Cited on pages 83, 113.)
- Haris, Mohd, Pavan Chakraborty, and B Venkata Rao (2015). “EMG signal based finger movement recognition for prosthetic hand control”. In: *2015 Communication, Control and Intelligent Systems (CCIS)*. IEEE, pp. 194–198. (Cited on page 35.)
- Hart, Sandra G. (Nov. 2006). “Nasa-Task Load Index (NASA-TLX); 20 Years Later:” in: *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* 50.9, pp. 904–908. (Cited on pages 28, 95.)
- Hart, Sandra G. and Lowell E. Staveland (Jan. 1988). “Development of NASA-TLX (Task Load Index): Results of Empirical and Theoretical Research”. In: *Advances in Psychology* 52.C, pp. 139–183. (Cited on pages 28, 65, 73, 95, 115.)
- Hashim, Nur Afiqah, Nasrul Anuar Abd Razak, and Noor Azuan Abu Osman (2021). “Comparison of Conventional and Virtual Reality Box and Blocks Tests in Upper Limb Amputees: A Case-Control Study”. In: *IEEE Access* 9, pp. 76983–76990. (Cited on page 21.)
- Hayward, Vincent (2018). “A Brief Overview of the Human Somatosensory System”. In: pp. 29–48. (Cited on page 62.)
- Hebert, Jacqueline S., Jaret L. Olson, Michael J. Morhart, Michael R. Dawson, Paul D. Marasco, Todd A. Kuiken, and K. Ming Chan (2014). “Novel targeted sensory reinnervation technique to restore functional hand sensation after transhumeral amputation”. In: *IEEE Transactions on Neural Systems and Rehabilitation Engineering* 22.4, pp. 765–773. (Cited on page 2.)
- Heerschop, Anniëk, Corry K. van der Sluis, Egbert Otten, and Raoul M. Bongers (Jan. 2020a). “Looking beyond proportional control: The relevance of mode switching in learning to operate multi-articulating myoelectric upper-limb prostheses”. In: *Biomedical Signal Processing and Control* 55, p. 101647. (Cited on page 7.)
- (Apr. 2020b). “Performance among different types of myocontrolled tasks is not related”. In: *Human Movement Science* 70, p. 102592. (Cited on page 20.)
- Hong, Yaoye, Yao Zhao, Joseph Berman, Yinding Chi, Yanbin Li, He Helen Huang, and Jie Yin (Aug. 2023). “Angle-programmed tendril-like trajectories enable a multifunctional gripper with ultradelicacy, ultrastrength, and ultraprecision”. In: *Nature Communications* 2023 14:1 14.1, pp. 1–10. (Cited on page 86.)

- Hu, Yu, Yongkang Wong, Wentao Wei, Yu Du, Mohan Kankanhalli, and Weidong Geng (2018). “A novel attention-based hybrid CNN-RNN architecture for sEMG-based gesture recognition”. In: *PloS one* 13.10, e0206049. (Cited on page 35.)
- Hudgins, Bernard, Philip Parker, and Robert N. Scott (1993). “A New Strategy for Multifunction Myoelectric Control”. In: *IEEE Transactions on Biomedical Engineering* 40.1, pp. 82–94. (Cited on pages 8, 34, 55.)
- Hunt, Chris, Rahul Yerrabelli, Caitlin Clancy, Luke Osborn, Rahul Kaliki, and Nitish Thakor (2017). “Pham: prosthetic hand assessment measure”. In: *Proceedings of the Myoelectric Control Symposium (MEC17)*, pp. 221–224. (Cited on page 94.)
- Hussaini, Ali and Peter J. Kyberd (June 2017). “Refined clothespin relocation test and assessment of motion”. In: *Prosthetics and Orthotics International* 41.3, pp. 294–302. (Cited on page 9.)
- Imaizumi, Shu, Tomohisa Asai, and Shinichi Koyama (Oct. 2016). “Embodied prosthetic arm stabilizes body posture, while unembodied one perturbs it”. In: *Consciousness and Cognition* 45, pp. 75–88. (Cited on page 79.)
- Jabbari, Milad, Rami N Khushaba, and Kianoush Nazarpour (2020). “Emg-based hand gesture classification with long short-term memory deep recurrent neural networks”. In: *2020 42nd Annual International Conference of the IEEE Engineering in Medicine & Biology Society (EMBC)*. IEEE, pp. 3302–3305. (Cited on page 35.)
- Jafarzadeh, M, D C Hussey, and Y Tadesse (Sept. 2019). “Deep learning approach to control of prosthetic hands with electromyography signals”. In: *2019 IEEE International Symposium on Measurement and Control in Robotics (ISMCR)*, pp. 1–4. (Cited on page 34.)
- Jebsen, Robert H, Neal Taylor, Roberta B Trieschmann, Martha J Trotter, and Linda A Howard (1969). “An objective and standardized test of hand function”. In: *Arch. Phys. Med. Rehabil.* 50.6, pp. 311–319. (Cited on pages 50, 68, 71, 94, 95, 97, 116.)
- Jiang, Ning, Ivan Vujaklija, Hubertus Rehbaum, Bernhard Graimann, and Dario Farina (2014). “Is accurate mapping of EMG signals on kinematics needed for precise online myoelectric control?” In: *IEEE Transactions on Neural Systems and Rehabilitation Engineering* 22.3, pp. 549–558. (Cited on page 2.)
- Jiang, Wan, François Tremblay, and C. Elaine Chapman (Nov. 2018). “Context-dependent tactile texture-sensitivity in monkey M1 and S1 cortex”. In: *Journal of Neurophysiology* 120.5, pp. 2334–2350. (Cited on page 61.)
- Johansen, Heidi, Kristin Østlie, Liv Øinæs Andersen, and Svend Rand-Hendriksen (Oct. 2015). “Adults with congenital limb deficiency in Norway: demographic and clinical features, pain and the use of health care and welfare services. A cross-sectional study”. In: *Disability and Rehabilitation* 37.22, pp. 2076–2082. (Cited on pages 1, 83.)

- Johansen, Heidi, Kristin Østlie, Liv Øinæs Andersen, and Svend Rand-Hendriksen (Nov. 2016). “Health-related quality of life in adults with congenital unilateral upper limb deficiency in Norway. A cross-sectional study”. In: *Disability and Rehabilitation* 38.23, pp. 2305–2314. (Cited on pages 1, 113.)
- Johansson, R. S. and G. Westling (Mar. 1987). “Signals in tactile afferents from the fingers eliciting adaptive motor responses during precision grip”. In: *Experimental Brain Research* 66.1, pp. 141–154. (Cited on page 92.)
- Johansson, Roland S. and J. Randall Flanagan (Apr. 2009). “Coding and use of tactile signals from the fingertips in object manipulation tasks”. In: *Nature Reviews Neuroscience* 2009 10:5 10.5, pp. 345–359. (Cited on page 12.)
- Jones, L. E. and J. H. Davidson (1999). “Save that arm: A study of problems in the remaining arm of unilateral upper limb amputees”. In: *Prosthetics and Orthotics International* 23.1, pp. 55–58. (Cited on pages 1, 83.)
- Jönsson, Stewe, Kerstin Caine-Winterberger, and Rickard Brøanemark (2011). “Osseointegration amputation prostheses on the upper limbs: methods, prosthetics and rehabilitation”. In: *Prosthetics and Orthotics International* 35.2, pp. 190–200. (Cited on page 2.)
- Kang, Long, Sang-Hwa Kim, and Byung-Ju Yi (Dec. 2021). “Modeling, Design, and Implementation of an Underactuated Gripper with Capability of Grasping Thin Objects”. In: *Machines* 2021, Vol. 9, Page 347 9.12, p. 347. (Cited on page 85.)
- Kate, Jelle ten, Gerwin Smit, and Paul Breedveld (Apr. 2017). “3D-printed upper limb prostheses: a review”. In: *Disability and Rehabilitation: Assistive Technology* 12.3, pp. 300–314. (Cited on page 2.)
- Kejlaa, G. H. (1992). “The social and economic outcome after upper limb amputation”. In: *Prosthetics and Orthotics International* 16.1, pp. 25–31. (Cited on page 36.)
- Kelly, Michael F., Philip A. Parker, and Robert N. Scott (1990). “The Application of Neural Networks to Myoelectric Signal Analysis: A Preliminary Study”. In: *IEEE Transactions on Biomedical Engineering* 37.3, pp. 221–230. (Cited on page 7.)
- Kershner, Irvin and George Lucas (1980). *Star Wars: Episode V – The Empire Strikes Back*. (Cited on pages 2, 88.)
- Kerver, Nienke, Verena Schuurmans, Corry K. van der Sluis, and Raoul M. Bongers (Feb. 2023). “The multi-grip and standard myoelectric hand prosthesis compared: does the multi-grip hand live up to its promise?” In: *Journal of NeuroEngineering and Rehabilitation* 2023 20:1 20.1, pp. 1–18. (Cited on page 2.)
- Kim, Uikyum, Dawoon Jung, Heeyoen Jeong, Jongwoo Park, Hyun Mok Jung, Joono Cheong, Hyouk Ryeol Choi, Hyunmin Do, and Chanhun Park (Dec. 2021). “Integrated linkage-driven dexterous

- anthropomorphic robotic hand”. In: *Nature Communications* 2021 12:1 12.1, pp. 1–13. (Cited on page 55.)
- Krasoulis, Agamemnon, Iris Kyranou, Mustapha Suphi Erden, Kianoush Nazarpour, and Sethu Vijayakumar (July 2017). “Improved prosthetic hand control with concurrent use of myoelectric and inertial measurements”. In: *Journal of NeuroEngineering and Rehabilitation* 14.1, pp. 1–14. (Cited on page 10.)
- Kristoffersen, Morten B., Andreas W. Franzke, Raoul M. Bongers, Michael Wand, Alessio Murgia, and Corry K. van der Sluis (Dec. 2021). “User training for machine learning controlled upper limb prostheses: a serious game approach”. In: *Journal of NeuroEngineering and Rehabilitation* 18.1, pp. 1–15. (Cited on page 20.)
- Kuiken, T A, G A Dumanian, R D Lipschutz, L A Miller, and K A Stubblefield (2004). “The use of targeted muscle reinnervation for improved myoelectric prosthesis control in a bilateral shoulder disarticulation amputee”. In: *Prosthetics and Orthotics International* 28.3, pp. 245–253. (Cited on page 2.)
- Kumar, Dinesh K, Beth Jelfs, Xiaohong Sui, and Sridhar P Arjunan (2019). “Prosthetic hand control: A multidisciplinary review to identify strengths, shortcomings, and the future”. In: *Biomedical Signal Processing and Control* 53, p. 101588. (Cited on pages 5, 34.)
- Kumar, Vikash and Emanuel Todorov (Dec. 2015). “MuJoCo HAPTIX: A virtual reality system for hand manipulation”. In: *IEEE-RAS International Conference on Humanoid Robots*. Vol. 2015-December. IEEE Computer Society, pp. 657–663. (Cited on page 21.)
- Kyberd, P. J. and P. H. Chappell (Nov. 1994). “The Southampton Hand: an intelligent myoelectric prosthesis.” In: *Journal of Rehabilitation Research and Development* 31.4, pp. 326–334. (Cited on pages 9, 82, 83.)
- Kyberd, Peter J. (Jan. 2021). “Making Hands: A History of Prosthetic Arms”. In: *Making Hands: A History of Prosthetic Arms*, pp. 1–364. (Cited on page 84.)
- Kyberd, Peter J., Alexandru Florin Popa, and Théo Cojean (Sept. 2023). “A Tool to Assist in the Analysis of Gaze Patterns in Upper Limb Prosthetic Use”. In: *Prosthesis 2023, Vol. 5, Pages 898-915* 5.3, pp. 898–915. (Cited on page 12.)
- Kyberd, Peter J., Constanze Wartenberg, Leif Sandsjö, Stewe Jönsson, David Gow, Joakim Frid, Christian Almström, and Lena Sperling (Apr. 2007). “Survey of upper-extremity prosthesis users in Sweden and the United Kingdom”. In: *Journal of Prosthetics and Orthotics* 19.2, pp. 55–62. (Cited on pages 55, 82.)
- Laffranchi, M., N. Boccardo, S. Traverso, L. Lombardi, M. Canepa, A. Lince, M. Semprini, J. A. Saglia, A. Naceri, R. Sacchetti, E. Gruppioni, and L. De Michieli (Sept. 2020). “The Hannes hand prosthesis replicates the key biological properties of the human hand”. In: *Science Robotics* 5.46, p. 467. (Cited on pages 9, 55, 83, 86.)

- Lee, Stan and Jack Kirby (May 1966). “Fantastic Four”. In: *Marvel Comics*. (Cited on pages 87, 88.)
- Light, C. M., P. H. Chappell, P. J. Kyberd, and B. S. Ellis (Jan. 1999). “A Critical Review of Functionality Assessment in Natural and Prosthetic Hands”. In: *British Journal of Occupational Therapy* 62.1, pp. 7–11. (Cited on page 94.)
- Light, Colin M., Paul H. Chappell, and Peter J. Kyberd (June 2002). “Establishing a standardized clinical assessment tool of pathologic and prosthetic hand function: Normative data, reliability, and validity”. In: *Archives of Physical Medicine and Rehabilitation* 83.6, pp. 776–783. (Cited on pages 28, 48, 94.)
- Liow, Lois, Angus B. Clark, and Nicolas Rojas (Apr. 2020). “OLYMPIC: A modular, tendon-driven prosthetic hand with novel finger and wrist coupling mechanisms”. In: *IEEE Robotics and Automation Letters* 5.2, pp. 299–306. (Cited on pages 9, 18, 21, 28, 46, 55, 62, 82, 83, 88, 89, 113.)
- Lu, Qiujie, Nicholas Baron, Angus B. Clark, and Nicolas Rojas (Dec. 2021). “Systematic object-invariant in-hand manipulation via reconfigurable underactuation: Introducing the RUTH gripper”. In: *International Journal of Robotics Research* 40.12-14, pp. 1402–1418. (Cited on page 85.)
- Lu, Qiujie, Angus B. Clark, Matthew Shen, and Nicolas Rojas (Apr. 2020). “An Origami-Inspired Variable Friction Surface for Increasing the Dexterity of Robotic Grippers”. In: *IEEE Robotics and Automation Letters* 5.2, pp. 2538–2545. (Cited on page 85.)
- Lukyanenko, Platon, Hendrik Adriaan Dewald, Joris Lambrecht, Robert F. Kirsch, Dustin J. Tyler, and Matthew R. Williams (Dec. 2021). “Stable, simultaneous and proportional 4-DoF prosthetic hand control via synergy-inspired linear interpolation: a case series”. In: *Journal of NeuroEngineering and Rehabilitation* 18.1, p. 50. (Cited on pages 2, 8, 56.)
- Ma, Raymond R. and Aaron M. Dollar (Apr. 2014). “An underactuated hand for efficient finger-gaiting-based dexterous manipulation”. In: *2014 IEEE International Conference on Robotics and Biomimetics, IEEE ROBIO 2014*, pp. 2214–2219. (Cited on page 98.)
- Maat, Bartjan, Gerwin Smit, Dick Plettenburg, and Paul Breedveld (Feb. 2018). “Passive prosthetic hands and tools: A literature review”. In: *Prosthetics and Orthotics International* 42.1, pp. 66–74. (Cited on page 84.)
- Maldonado, Andrés A., Michelle F. Kircher, Robert J. Spinner, Allen T. Bishop, and Alexander Y. Shin (Mar. 2016). “The role of elective amputation in patients with traumatic brachial plexus injury”. In: *Journal of Plastic, Reconstructive & Aesthetic Surgery* 69.3, pp. 311–317. (Cited on page 3.)
- Malone, J M, L L Fleming, J Roberson, T E Whitesides Jr, J M Leal, J U Poole, and R Sternstein Grodin (May 1984). “Immediate, Early, and Late Postsurgical Management of Upper-Limb Amputation”. In: *Journal of Rehabilitation Research and Development* 21.1, pp. 33–41. (Cited on page 2.)

- Marasco, Paul D., Jacqueline S. Hebert, Jon W. Sensinger, Courtney E. Shell, Jonathon S. Schofield, Zachary C. Thumser, Raviraj Nataraj, Dylan T. Beckler, Michael R. Dawson, Dan H. Blustein, Satinder Gill, Brett D. Mensh, Rafael Granja-Vazquez, Madeline D. Newcomb, Jason P. Carey, and Beth M. Orzell (Mar. 2018). “Illusory movement perception improves motor control for prosthetic hands”. In: *Science Translational Medicine* 10.432, p. 6990. (Cited on page 12.)
- Marasco, Paul D., Jacqueline S. Hebert, Jonathon W. Sensinger, Dylan T. Beckler, Zachary C. Thumser, Ahmed W. Shehata, Heather E. Williams, and Kathleen R. Wilson (Sept. 2021). “Neurobotic fusion of prosthetic touch, kinesthesia, and movement in bionic upper limbs promotes intrinsic brain behaviors”. In: *Science Robotics* 6.58, p. 3368. (Cited on pages 2, 12, 56.)
- Marinelli, A., N. Boccardo, M. Canepa, D. Di Domenico, M. Semprini, M. Chiappalone, M. Laffranchi, L. De Michieli, and S. Dosen (2023). “A Novel Method for Vibrotactile Proprioceptive Feedback Using Spatial Encoding and Gaussian Interpolation”. In: *IEEE Transactions on Biomedical Engineering*. (Cited on page 63.)
- McDonald, Cody L., Sarah Westcott-Mccoy, Marcia R. Weaver, Juanita Haagsma, and Deborah Kartin (Apr. 2021). “Global prevalence of traumatic non-fatal limb amputation”. In: *Prosthetics and Orthotics International* 45.2, pp. 105–114. (Cited on pages 1, 3.)
- Michael, Robert R. and Fred R. Crawford (July 1963). “Myoelectric surface potentials for machine control”. In: *Electrical Engineering* 82.11, pp. 689–691. (Cited on pages 2, 82.)
- Miller, George (2015). *Mad Max: Fury Road*. (Cited on page 2.)
- Miller, Laura A., Kathy A. Stubblefield, Robert D. Lipschutz, Blair A. Lock, and Todd A. Kuiken (Feb. 2008). “Improved myoelectric prosthesis control using targeted reinnervation surgery: A case series”. In: *IEEE Transactions on Neural Systems and Rehabilitation Engineering* 16.1, pp. 46–50. (Cited on page 2.)
- Mohammadi, Alireza, Jim Lavranos, Ying Tan, Peter Choong, and Denny Oetomo (2022). “Preliminary Clinical Evaluation of the X-Limb Hand: A 3D Printed Soft Robotic Hand Prosthesis”. In: *Biosystems and Biorobotics* 28, pp. 869–873. (Cited on page 92.)
- Mohammadi, Alireza, Jim Lavranos, Hao Zhou, Rahim Mutlu, Gursel Alici, Ying Tan, Peter Choong, and Denny Oetomo (May 2020). “A practical 3D-printed soft robotic prosthetic hand with multi-articulating capabilities”. In: *PLOS ONE* 15.5, e0232766. (Cited on page 55.)
- Mouazé, Nicolas and Lionel Birglen (Apr. 2022). “Bistable compliant underactuated gripper for the gentle grasp of soft objects”. In: *Mechanism and Machine Theory* 170, p. 104676. (Cited on page 101.)
- Murguialday, Ander Ramos, Vikram Aggarwal, Aniruddha Chatterjee, Yoonju Cho, Robert Rasmussen, Brandon O’Rourke, Soumyadipta Acharya, and Nitish V. Thakor (2007). “Brain-computer interface for a prosthetic hand using local machine control and haptic feedback”. In: *2007 IEEE*

- 10th International Conference on Rehabilitation Robotics, ICORR'07, pp. 609–613. (Cited on page 5.)
- Nazmi, Nurhazimah, Mohd Azizi Abdul Rahman, Shin-ichiroh Yamamoto, Siti Anom Ahmad, MB Malarvili, Saiful Amri Mazlan, and Hairi Zamzuri (Oct. 2017). “Assessment on Stationarity of EMG Signals with Different Windows Size During Isotonic Contractions”. In: *Applied Sciences 2017, Vol. 7, Page 1050* 7.10, p. 1050. (Cited on page 42.)
- Nguyen, Anh Tuan, Markus W Drealan, Diu Khue Luu, Ming Jiang, Jian Xu, Jonathan Cheng, Qi Zhao, Edward W Keefer, and Zhi Yang (2021). “A portable, self-contained neuroprosthetic hand with deep learning-based finger control”. In: *Journal of neural engineering* 18.5, p. 056051. (Cited on page 35.)
- Nissler, Christian, Markus Nowak, Mathilde Connan, Stefan Büttner, Jörg Vogel, Ingo Kossyk, Zoltán-Csaba Márton, and Claudio Castellini (Mar. 2019). “VITA—an everyday virtual reality setup for prosthetics and upper-limb rehabilitation”. In: *Journal of Neural Engineering* 16.2, p. 026039. (Cited on pages 18, 20, 21.)
- O’Keeffe, Bernard (May 2011). “Prosthetic rehabilitation of the upper limb amputee”. In: *Indian Journal of Plastic Surgery : Official Publication of the Association of Plastic Surgeons of India* 44.2, p. 246. (Cited on pages 17, 20.)
- Ortiz-Catalan, Max, Rickard Brånemark, Bo Håkansson, and Jean Delbeke (June 2012). “On the viability of implantable electrodes for the natural control of artificial limbs: Review and discussion”. In: *BioMedical Engineering Online* 11.1, pp. 1–24. (Cited on page 2.)
- Ortiz-Catalan, Max, Jan Zbinden, Jason Millenaar, Daniele D’Accolti, Marco Controzzi, Francesco Clemente, Leonardo Cappello, Eric J. Earley, Enzo Mastinu, Justyna Kolankowska, Maria Munoz-Novoa, Stewe Jönsson, Christian Cipriani, Paolo Sassu, and Rickard Brånemark (Oct. 2023). “A highly integrated bionic hand with neural control and feedback for use in daily life”. In: *Science Robotics* 8.83. (Cited on page 2.)
- Østlie, Kristin, Rosemary J. Franklin, Ola H. Skjeldal, Anders Skrondal, and Per Magnus (Dec. 2011a). “Musculoskeletal Pain and Overuse Syndromes in Adult Acquired Major Upper-Limb Amputees”. In: *Archives of Physical Medicine and Rehabilitation* 92.12, pp. 1967–1973. (Cited on page 1.)
- Østlie, Kristin, Ingrid Marie Lesjø, Rosemary Joy Franklin, Beate Garfelt, Ola Hunsbeth Skjeldal, and Per Magnus (July 2012). “Prosthesis rejection in acquired major upper-limb amputees: a population-based survey”. In: *Disability and Rehabilitation: Assistive Technology* 7.4, pp. 294–303. (Cited on pages 55, 82.)
- Østlie, Kristin, Per Magnus, Ola H. Skjeldal, Beate Garfelt, and Kristian Tambs (2011b). “Mental health and satisfaction with life among upper limb amputees: a Norwegian population-based survey comparing adult acquired major upper limb amputees with a control group”. In: *Disability and Rehabilitation* 33.17-18, pp. 1594–1607. (Cited on pages 1, 113.)

- Østlie, Kristin, Ola H. Skjeldal, Beate Garfelt, and Per Magnus (2011c). “Adult acquired major upper limb amputation in Norway: prevalence, demographic features and amputation specific features. A population-based survey”. In: *Disability and Rehabilitation* 33.17-18, pp. 1636–1649. (Cited on pages 36, 83, 113.)
- Osumi, Michihiro, Kazunori Inomata, Yuji Inoue, Yuko Otake, Shu Morioka, and Masahiko Sumitani (May 2019). “Characteristics of Phantom Limb Pain Alleviated with Virtual Reality Rehabilitation”. In: *Pain Medicine* 20.5, pp. 1038–1046. (Cited on pages 18, 20.)
- Parajuli, Nawadita, Neethu Sreenivasan, Paolo Bifulco, Mario Cesarelli, Sergio Savino, Vincenzo Niola, Daniele Esposito, Tara J Hamilton, Ganesh R Naik, Upul Gunawardana, et al. (2019). “Real-time EMG based pattern recognition control for hand prostheses: a review on existing methods, challenges and future implementation”. In: *Sensors* 19.20, p. 4596. (Cited on page 35.)
- Parr, Johnny V.V., Adam Galpin, Liis Uiga, Ben Marshall, David J. Wright, Zoe C. Franklin, and Greg Wood (May 2023). “A tool for measuring mental workload during prosthesis use: The Prosthesis Task Load Index (PROS-TLX)”. In: *PLOS ONE* 18.5, e0285382. (Cited on pages 12, 94.)
- Paskett, Michael D., Tyler S. Davis, Troy N. Tully, Mark R. Brinton, and Gregory A. Clark (2021). “Portable System for Home Use Enables Closed-Loop, Continuous Control of Multi-Degree-of-Freedom Bionic Arm”. In: *Proceedings of the Annual International Conference of the IEEE Engineering in Medicine and Biology Society, EMBS*. Institute of Electrical and Electronics Engineers Inc., pp. 6608–6612. (Cited on pages 2, 56.)
- Pasquina, Paul F., Melissa Evangelista, A. J. Carvalho, Joseph Lockhart, Sarah Griffin, George Nanos, Patricia McKay, Morten Hansen, Derek Ipsen, James Vandersea, Josef Butkus, Matthew Miller, Ian Murphy, and David Hankin (Apr. 2015). “First-in-man demonstration of a fully implanted myoelectric sensors system to control an advanced electromechanical prosthetic hand”. In: *Journal of Neuroscience Methods* 244, pp. 85–93. (Cited on page 2.)
- Peck, Tabitha C. and Mar Gonzalez-Franco (Feb. 2021). “Avatar Embodiment. A Standardized Questionnaire”. In: *Frontiers in Virtual Reality* 0, p. 44. (Cited on page 65.)
- Phelan, Ivan, Madelynne Arden, Maria Matsangidou, Alicia Carrion-Plaza, and Shirley Lindley (2021). “Designing a Virtual Reality Myoelectric Prosthesis Training System for Amputees; Designing a Virtual Reality Myoelectric Prosthesis Training System for Amputees”. In: *Extended Abstracts of the 2021 CHI Conference on Human Factors in Computing Systems*. (Cited on pages 18, 20, 21.)
- Postema, Sietke G., Raoul M. Bongers, Michael A. Brouwers, Helena Burger, Liselotte M. Norling-Hermansson, Michiel F. Reneman, Pieter U. Dijkstra, and Corry K. van der Sluis (June 2016). “Upper Limb Absence: Predictors of Work Participation and Work Productivity”. In: *Archives of Physical Medicine and Rehabilitation* 97.6, pp. 892–899. (Cited on pages 1, 83.)

- Prahm, Cosima, Fares Kayali, and Oskar Aszmann (Aug. 2019). “MyoBeatz: Using music and rhythm to improve prosthetic control in a mobile game for health”. In: *2019 IEEE 7th International Conference on Serious Games and Applications for Health, SeGAH 2019*. (Cited on page 20.)
- Prahm, Cosima, Fares Kayali, Ivan Vujaklija, Agnes Sturma, and Oskar Aszmann (Aug. 2017). “Increasing motivation, effort and performance through game-based rehabilitation for upper limb myoelectric prosthesis control”. In: *International Conference on Virtual Rehabilitation, ICVR 2017*-June. (Cited on page 20.)
- Puhaindran, Mark E., Joanne Chou, Jonathan A. Forsberg, and Edward A. Athanasian (June 2012). “Major Upper-Limb Amputations for Malignant Tumors”. In: *The Journal of Hand Surgery* 37.6, pp. 1235–1241. (Cited on page 3.)
- Pylatiuk, Christian, Stefan Schulz, and Leonhard Döderlein (Dec. 2007). “Results of an internet survey of myoelectric prosthetic hand users”. In: *Prosthetics and Orthotics International* 31.4, pp. 362–370. (Cited on pages 55, 82.)
- Rahimian, Elahe, Soheil Zabihi, Amir Asif, Dario Farina, Seyed Farokh Atashzar, and Arash Mohammadi (2021). “FS-HGR: Few-shot Learning for Hand Gesture Recognition via ElectroMyography”. In: *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, pp. 1–1. (Cited on pages 8, 13, 35.)
- Raimi, Sam and Scott Spiegel (Mar. 1987). *Evil Dead II*. (Cited on page 88.)
- Reaz, Mamun Bin Ibne, M Sazzad Hussain, and Faisal Mohd-Yasin (2006). “Techniques of EMG signal analysis: detection, processing, classification and applications”. In: *Biological procedures online* 8.1, pp. 11–35. (Cited on pages 2, 8.)
- Reiter, Reinhold (1948). “Eine neue elektrokunsthand”. In: *Grenzgebiete der Medizin*. (Cited on pages 2, 5.)
- Resnik, Linda, Heather Benz, Matthew Borgia, and Melissa A. Clark (Dec. 2019). “Patient Perspectives on Osseointegration: A National Survey of Veterans with Upper Limb Amputation”. In: *Physical Medicine & Rehabilitation* 11.12, pp. 1261–1271. (Cited on page 2.)
- Resnik, Linda, Matthew Borgia, Jill Cancio, Jeffrey Heckman, Jason Highsmith, Charles Levy, Samuel Phillips, and Joseph Webster (2020). “Dexterity, activity performance, disability, quality of life, and independence in upper limb Veteran prosthesis users: a normative study”. In: *Disability and Rehabilitation* 44.11, pp. 2470–2481. (Cited on page 55.)
- Resnik, Linda, Katherine Etter, Shana Lieberman Klinger, and Charles Kambe (2011). “Using virtual reality environment to facilitate training with advanced upper-limb prosthesis”. In: *Journal of Rehabilitation Research and Development* 48.6, pp. 707–718. (Cited on page 18.)
- Resnik, Linda, Shana L. Klinger, and Katherine Etter (Dec. 2014). “The DEKA Arm: Its features, functionality, and evolution during the veterans affairs study to optimize the DEKA Arm”. In: *Prosthetics and Orthotics International* 38.6, pp. 492–504. (Cited on page 88.)

- Resnik, Linda, Marissa R Meucci, Shana Lieberman-Klinger, Christopher Fantini, Debra L Kelty, Roxanne Disla, and Nicole Sasson (2012). “Advanced Upper Limb Prosthetic Devices: Implications for Upper Limb Prosthetic Rehabilitation”. In: *Archives of Physical Medicine and Rehabilitation* 93.4, pp. 710–717. (Cited on pages 17, 18, 20.)
- Resnik, Linda J., Matthew L. Borgia, Frantzy Acluche, Jill M. Cancio, Gail Latlief, and Nicole Sasson (Jan. 2018). “How do the outcomes of the DEKA Arm compare to conventional prostheses?” In: *PLOS ONE* 13.1, e0191326. (Cited on page 92.)
- Roche, Aidan D., Hubertus Rehbaum, Dario Farina, and Oskar C. Aszmann (Mar. 2014). “Prosthetic Myoelectric Control Strategies: A Clinical Perspective”. In: *Current Surgery Reports* 2.3, pp. 1–11. (Cited on page 20.)
- Roeschlein, R. A. and E. Domholdt (Apr. 1989). “Factors related to successful upper extremity prosthetic use”. In: *Prosthetics and Orthotics International* 13.1, pp. 14–18. (Cited on page 17.)
- Rojas, Nicolas and Aaron M. Dollar (Aug. 2016). “Gross Motion Analysis of Fingertip-Based Within-Hand Manipulation”. In: *IEEE Transactions on Robotics* 32.4, pp. 1009–1016. (Cited on page 99.)
- Rojas, Nicolas, Raymond R. Ma, and Aaron M. Dollar (June 2016). “The GR2 Gripper: An Underactuated Hand for Open-Loop In-Hand Planar Manipulation”. In: *IEEE Transactions on Robotics* 32.3, pp. 763–770. (Cited on page 85.)
- Rossi, Matteo, Simone Benatti, Elisabetta Farella, and Luca Benini (2015). “Hybrid EMG classifier based on HMM and SVM for hand gesture recognition in prosthetics”. In: *2015 IEEE International Conference on Industrial Technology (ICIT)*. IEEE, pp. 1700–1705. (Cited on pages 34, 35.)
- Rossi, Matteo, Matteo Bianchi, Edoardo Battaglia, Manuel G. Catalano, and Antonio Bicchi (Jan. 2019). “HapPro: A Wearable Haptic Device for Proprioceptive Feedback”. In: *IEEE Transactions on Biomedical Engineering* 66.1, pp. 138–149. (Cited on page 57.)
- Rubner, Yossi, Carlo Tomasi, and Leonidas J Guibas (2000). “The earth mover’s distance as a metric for image retrieval”. In: *International journal of computer vision* 40.2, pp. 99–121. (Cited on page 44.)
- Salminger, Stefan, Heiko Stino, Lukas H. Pichler, Clemens Gstoettner, Agnes Sturma, Johannes A. Mayer, Michael Szivak, and Oskar C. Aszmann (2020). “Current rates of prosthetic usage in upper-limb amputees – have innovations had an impact on device acceptance?” In: *Disability and Rehabilitation* 44.14, pp. 3708–3713. (Cited on pages 2, 4, 55, 79, 82, 83, 94.)
- Salminger, Stefan, Agnes Sturma, Aidan D. Roche, Johannes A. Mayer, Clemens Gstoettner, and Oskar C. Aszmann (Dec. 2019). “Outcomes, Challenges, and Pitfalls after Targeted Muscle Reinnervation in High-Level Amputees: Is It Worth the Effort?” In: *Plastic and reconstructive surgery* 144.6, 1037e–1043e. (Cited on page 2.)

- Samadani, Ali (2018). “Gated recurrent neural networks for EMG-based hand gesture classification. A comparative study”. In: *2018 40th annual international conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*. IEEE, pp. 1–4. (Cited on page 35.)
- Saridis, George N. and Thomas P. Gootee (1982). “EMG Pattern Analysis and Classification for a Prosthetic Arm”. In: *IEEE Transactions on Biomedical Engineering* BME-29.6, pp. 403–412. (Cited on page 8.)
- Sensinger, Jonathon W. and Strahinja Dosen (June 2020). “A Review of Sensory Feedback in Upper-Limb Prostheses From the Perspective of Human Motor Control”. In: *Frontiers in Neuroscience* 14, p. 345. (Cited on page 77.)
- Shaw, Laxmi and Sangeeta Bagha (2012). “Online EMG signal analysis for diagnosis of neuromuscular diseases by using PCA and PNN”. In: *International Journal of Engineering Science and Technology (IJEST)* 4.10, pp. 4453–4459. (Cited on page 38.)
- Sherman, E. D. (Dec. 1964). “A Russian Bioelectric-Controlled Prosthesis: Report of a Research Team from the Rehabilitation Institute of Montreal”. In: *Canadian Medical Association Journal* 91.24, p. 1268. (Cited on pages 2, 6, 82.)
- Simão, Miguel, Pedro Neto, and Olivier Gibaru (2019). “EMG-based online classification of gestures with recurrent neural networks”. In: *Pattern Recognition Letters* 128, pp. 45–51. (Cited on page 35.)
- Sluis, Corry K. van der, Paul P. Hartman, Tanneke Schoppen, and Pieter U. Dijkstra (Jan. 2009). “Job Adjustments, Job Satisfaction and Health Experience in Upper and Lower Limb Amputees”. In: *Prosthetics and Orthotics International* 33.1, pp. 41–51. (Cited on pages 36, 83.)
- Smail, Lauren C., Chantelle Neal, Courtney Wilkins, and Tara L. Packham (2020). “Comfort and function remain key factors in upper limb prosthetic abandonment: findings of a scoping review”. In: *Disability and Rehabilitation: Assistive Technology* 16.8, pp. 821–830. (Cited on page 34.)
- Smit, Gerwin, Raoul M. Bongers, Corry K. Van der Sluis, and Dick H. Plettenburg (June 2012). “Efficiency of voluntary opening hand and hook prosthetic devices: 24 years of development?” In: *Journal of rehabilitation research and development* 49.4, pp. 523–534. (Cited on pages 55, 84.)
- Smit, Gerwin and Dick H. Plettenburg (Dec. 2010). “Efficiency of voluntary closing hand and hook prostheses”. In: *Prosthetics and Orthotics International* 34.4, pp. 411–427. (Cited on pages 55, 84.)
- Smurr, Lisa M., Kristin Gulick, Kathleen Yancosek, and Oren Ganz (Apr. 2008). “Managing the Upper Extremity Amputee: A Protocol for Success”. In: *Journal of Hand Therapy* 21.2, pp. 160–176. (Cited on pages 17, 18, 20.)
- Snow, Peter W, Imad Sedki, Marco Sinisi, Richard Comley, and Rui C V Loureiro (Aug. 2017). “Robotic therapy for phantom limb pain in upper limb amputees”. In: *IEEE ... International Conference on Rehabilitation Robotics : [proceedings] 2017*, pp. 1019–1024. (Cited on pages 18, 20, 21.)

- Sobinov, Anton R. and Sliman J. Bensmaia (Oct. 2021). “The neural mechanisms of manual dexterity”. In: *Nature Reviews Neuroscience* 2021 22, pp. 741–757. (Cited on pages 12, 55, 61, 64, 83.)
- Spiers, Adam, Jillian Cochran, Linda Resnik, and Aaron Dollar (Apr. 2021). “Quantifying Prosthetic and Intact Limb Use in Upper Limb Amputees via Egocentric Video: An Unsupervised, At-Home Study”. In: *IEEE Transactions on Medical Robotics and Bionics*, pp. 1–1. (Cited on page 10.)
- Spiers, Adam J., Berk Calli, and Aaron M. Dollar (Oct. 2018). “Variable-Friction Finger Surfaces to Enable Within-Hand Manipulation via Gripping and Sliding”. In: *IEEE Robotics and Automation Letters* 3.4, pp. 4116–4123. (Cited on page 85.)
- Stavenhuetter, Ronald A.J., Lionel Birglen, and Just L. Herder (June 2017). “A planar underactuated grasper with adjustable compliance”. In: *Mechanism and Machine Theory* 112, pp. 295–306. (Cited on page 101.)
- Tam, Simon, Mounir Boukadoum, Alexandre Campeau-Lecours, and Benoit Gosselin (2019). “A fully embedded adaptive real-time hand gesture classifier leveraging HD-sEMG and deep learning”. In: *IEEE transactions on biomedical circuits and systems* 14.2, pp. 232–243. (Cited on pages 34, 35.)
- Tavakoli, Mahmoud, Carlo Benussi, Pedro Alhais Lopes, Luis Bica Osorio, and Anibal T de Almeida (2018). “Robust hand gesture recognition with a double channel surface EMG wearable armband and SVM classifier”. In: *Biomedical Signal Processing and Control* 46, pp. 121–130. (Cited on page 34.)
- Tchimino, Jack, Jakob Lund Dideriksen, and Strahinja Dosen (Dec. 2023). “EMG feedback improves grasping of compliant objects using a myoelectric prosthesis”. In: *Journal of NeuroEngineering and Rehabilitation* 20.1, pp. 1–14. (Cited on page 10.)
- Tiffin, Joseph and Eston J Asher (1948). “The Purdue Pegboard: norms and studies of reliability and validity.” In: *Journal of applied psychology* 32.3, p. 234. (Cited on page 94.)
- Townsend, William (June 2000). “The BarrettHand grasper – programmably flexible part handling and assembly”. In: *Industrial Robot: An International Journal* 27.3, pp. 181–188. (Cited on page 85.)
- Trent, Lauren, Michelle Intintoli, Pat Prigge, Chris Bollinger, Lisa Smurr Walters, Dan Conyers, John Miguelez, and Tiffany Ryan (Aug. 2019). “A narrative review: current upper limb prosthetic options and design”. In: *Disability and Rehabilitation: Assistive Technology* 15.6, pp. 604–613. (Cited on pages 4, 5, 87.)
- Trombly, Catherine A and Anna Deane Scott (1983). *Occupational Therapy for Physical Dysfunction*. 2nd ed. Baltimore: Williams and Wilkins, p. 57. (Cited on pages 9, 19, 28, 68, 71, 94, 115.)
- Tsinganos, Panagiotis, Bruno Cornelis, J Cornelis, Bart Jansen, and Athanassios Skodras (June 2018). “Deep Learning in EMG-based Gesture Recognition”. In: *5th International Conference on Physiological Computing Systems*, pp. 107–114. (Cited on page 34.)
- Tuffield, Paul and Hugo Elias (2003). “The Shadow robot mimics human actions”. In: *Industrial Robot* 30.1, pp. 56–60. (Cited on page 55.)

- Uellendahl, Jack (Oct. 2017). “Myoelectric versus Body-Powered Upper-Limb Prostheses: A Clinical Perspective”. In: *JPO Journal of Prosthetics and Orthotics* 29.4S, pp. 25–29. (Cited on page 97.)
- Umeda, Tatsuya, Tadashi Isa, and Yukio Nishimura (2019). “The somatosensory cortex receives information about motor output”. In: *Science Advances* 5.7. (Cited on page 61.)
- Vargas, Luis, He Helen Huang, Yong Zhu, and Xiaogang Hu (Dec. 2021). “Closed-loop control of a prosthetic finger via evoked proprioceptive information”. In: *Journal of Neural Engineering* 18.6, p. 066029. (Cited on page 57.)
- Vargesson, Neil (June 2015). “Thalidomide-induced teratogenesis: History and mechanisms”. In: *Birth Defects Research Part C: Embryo Today: Reviews* 105.2, pp. 140–156. (Cited on page 3.)
- Vujaklija, Ivan, Moon Ki Jung, Timothy Hasenoehrl, Aidan D. Roche, Agnes Sturma, Silvia Muceli, Richard Crevenna, Oskar C. Aszmann, and Dario Farina (Mar. 2023). “Biomechanical Analysis of Body Movements of Myoelectric Prosthesis Users During Standardized Clinical Tests”. In: *IEEE Transactions on Biomedical Engineering* 70.3, pp. 789–799. (Cited on page 94.)
- Waris, Asim, Imran Khan Niazi, Mohsin Jamil, Omer Gilani, Kevin Englehart, Winnie Jensen, Muhammad Shafique, and Ernest Nlandu Kamavuako (2018). “The effect of time on EMG classification of hand motions in able-bodied and transradial amputees”. In: *Journal of Electromyography and Kinesiology* 40, pp. 72–80. (Cited on page 35.)
- Wattanasiri, Panipat, Pairat Tangpornprasert, and Chanyaphan Virulsri (June 2018). “Design of multi-grip patterns prosthetic hand with single actuator”. In: *IEEE Transactions on Neural Systems and Rehabilitation Engineering* 26.6, pp. 1188–1198. (Cited on page 83.)
- Watve, Sachin, Greg Dodd, Ruth MacDonald, and Elizabeth R. Stoppard (Apr. 2011). “Upper limb prosthetic rehabilitation”. In: *Orthopaedics and Trauma* 25.2, pp. 135–142. (Cited on page 20.)
- Weiner, Pascal, Julia Starke, Felix Hundhausen, Jonas Beil, and Tamim Asfour (Dec. 2018). “The KIT Prosthetic Hand: Design and Control”. In: *IEEE International Conference on Intelligent Robots and Systems*, pp. 3328–3334. (Cited on pages 55, 82, 83, 86.)
- Widehammar, Cathrine, Kajsa Lidström Holmqvist, and Liselotte Hermansson (Oct. 2021). “Training for users of myoelectric multigrip hand prostheses: A scoping review”. In: *Prosthetics and Orthotics International* 45.5, pp. 393–400. (Cited on page 2.)
- Wilson, Samuel and Ravi Vaidyanathan (Aug. 2017). “Upper-limb prosthetic control using wearable multichannel mechanomyography”. In: *IEEE International Conference on Rehabilitation Robotics*, pp. 1293–1298. (Cited on page 5.)
- Xia, Peng, Jie Hu, and Yinghong Peng (2018). “EMG-based estimation of limb movement using deep learning with recurrent convolutional neural networks”. In: *Artificial organs* 42.5, E67–E77. (Cited on page 35.)
- Xiloyannis, Michele, Constantinos Gavriel, Andreas A.C. Thomik, and A. Aldo Faisal (Oct. 2017). “Gaussian Process Autoregression for Simultaneous Proportional Multi-Modal Prosthetic Control

- with Natural Hand Kinematics”. In: *IEEE Transactions on Neural Systems and Rehabilitation Engineering* 25.10, pp. 1785–1801. (Cited on pages 9, 13.)
- Yang, Zeyu, Angus B. Clark, Digby Chappell, and Nicolas Rojas (May 2022). “Instinctive Real-time sEMG-based Control of Prosthetic Hand with Reduced Data Acquisition and Embedded Deep Learning Training”. In: *2022 International Conference on Robotics and Automation (ICRA)*. IEEE, pp. 5666–5672. (Cited on pages 15, 33, 36, 50, 57.)
- Yoshikawa, Masahiro, Kazunori Ogawa, Shunji Yamanaka, and Noritaka Kawashima (2023). “Finch: Prosthetic Arm With Three Opposing Fingers Controlled by a Muscle Bulge”. In: *IEEE Transactions on Neural Systems and Rehabilitation Engineering* 31, pp. 377–386. (Cited on pages 9, 86.)
- Zanghieri, Marcello, Simone Benatti, Alessio Burrello, Victor Kartsch, Francesco Conti, and Luca Benini (2019). “Robust real-time embedded EMG recognition framework using temporal convolutional networks on a multicore IoT processor”. In: *IEEE transactions on biomedical circuits and systems* 14.2, pp. 244–256. (Cited on pages 34, 35.)
- Zollo, Loredana, Giovanni Di Pino, Anna L. Ciano, Federico Ranieri, Francesca Cordella, Cosimo Gentile, Emiliano Noce, Rocco A. Romeo, Alberto Dellacasa Bellingegni, Gianluca Vadalà, Sandra Miccinilli, Alessandro Mioli, Lorenzo Diaz-Balzani, Marco Bravi, Klaus P. Hoffmann, Andreas Schneider, Luca Denaro, Angelo Davalli, Emanuele Gruppioni, Rinaldo Sacchetti, Simona Castellano, Vincenzo Di Lazzaro, Silvia Sterzi, Vincenzo Denaro, and Eugenio Guglielmelli (Feb. 2019). “Restoring tactile sensations via neural interfaces for real-time force-and-slippage closed-loop control of bionic hands”. In: *Science Robotics* 4.27. (Cited on pages 2, 56.)
- Zuo, Kevin J. and Jaret L. Olson (Mar. 2014). “The evolution of functional hand replacement: From iron prostheses to hand transplantation”. In: *Plastic Surgery* 22.1, pp. 44–51. (Cited on page 5.)

Appendix A

Appendix for Achieving Continuous Control

A.1 Tables

ID	Age	Gender	Affected Side	ULD Level	Cause	Years Since	Dominant Hand	Own Prosthesis	Frequency of Use	Session Format
001	26	Male	Right	Below Elbow*§	C (TI)	26 (8)	Right	Cosmetic	Infrequent	Single
002	54	Male	Left	Below Elbow	PS	5	Right	None	-	Single
003	30	Male	Left	Below Elbow	C	30	Right	None	-	Single
004	42	Male	Both (Right)	Below Elbow	TI	9	Left	Body-Powered	Daily	Multiple
005	31	Male	Right	Below Elbow†	C	31	Right	Static	Infrequent	Single
006	30	Male	Right	Below Elbow	C	30	Right	None	-	Single
007	30	Male	Left	Below Elbow	C	28	Right	Static	Frequent	Multiple
008	45	Female	Right	Below Elbow‡	TI (PS)	24 (6)	Left	Static	Infrequent	Single
009	22	Male	Left	Below Elbow†	C	22	Right	Static	Frequent	Single
010	62	Male	Left	Below Elbow§	TI	3	Right	Static	Infrequent	Single

Table A.1: Table of participant characteristics of individual participants with limb difference. For bilateral upper limb differences the side tested is shown in brackets, and details for the tested side are shown. Causes listed: congenital (C), traumatic injury (TI), planned surgery (PS). *Participant 002 acquired a higher level of ULD than their congenital level from further traumatic injury; the muscles of the upper arm were used as an alternative input. †Participants 005 and 009 were only able to activate two muscles in their residual limb. ‡Participant 008 acquired their ULD via planned surgery after a prior traumatic injury, and received targeted muscle reinnervation; the muscles of the upper arm were used. §Participants 001 and 010 had no functioning elbow joint.

	OLDC	CLDC	OLCC	CLCC	All
Age/years	26.1 (5.7)	24.4 (2.5)	23.6 (6.4)	22.7 (3.1)	24.2 (4.6)
Male	6	6	5	6	23
Female	1	1	1	1	4
Right Handed	6	5	7	7	25
Left Handed	1	2	0	0	3

Table A.2: Characteristics of groups of participants without limb difference. Age, gender, and handedness of groups of participants without limb difference. For age, standard deviation is shown in brackets.

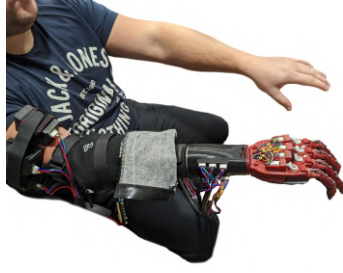
Item	Question	Adapted From
1	“The prosthesis is my hand”	[Bekrater-Bodmann 2020]
2	“The prosthesis belongs to me”	[Bekrater-Bodmann 2020]
3	“The prosthesis is part of my body”	[Bekrater-Bodmann 2020]
4	“The prosthesis resembles my body in terms of skin tone, freckles, or other visual features”	[Bekrater-Bodmann 2020]
5	“I feel as if I am looking directly at my own hand, rather than at a prosthesis”	[Bekrater-Bodmann 2020]
6	“My body feels complete”	[Bekrater-Bodmann 2020]
7	“The prosthesis is in the location where I would expect my hand to be”	[Bekrater-Bodmann 2020]
8	“The posture of the prosthesis corresponds to that of a real hand”	[Bekrater-Bodmann 2020]
9	“I felt a touch sensation in the prosthesis”	[Bekrater-Bodmann 2020]
10	“I could feel the position of the prosthesis”	—
11	“I could feel the force being applied by the prosthesis”	—
12	“The prosthesis moves the way I want it to move”	[Bekrater-Bodmann 2020]
13	“I am in control of the prosthesis”	[Bekrater-Bodmann 2020]
14	“The movement of the prosthesis feels like an actual movement”	[Bekrater-Bodmann 2020]

Table A.3: Prosthesis Embodiment Questionnaire for Upper Limb Prostheses. The questionnaire used to assess prosthesis embodiment for upper limb prostheses. Each question is answered using a 7-point Likert scale.

A.2 Figures



Figure A.1: Experimental setup for each participant with limb difference. Experimental setup for each participant with limb difference for stages 1 and 2 (left), and 3 (right). During stages 1 and 2, participants wore only the electrode armband and haptic feedback armband, while the prosthetic hand was desk-mounted. During stage 3, participants also donned the prosthetic hand. Note that participant 001 used an elastic sling to support the prosthesis due to having a short residual limb, and wore the haptic feedback armband on the opposing arm during stage 3 due to space constraints.



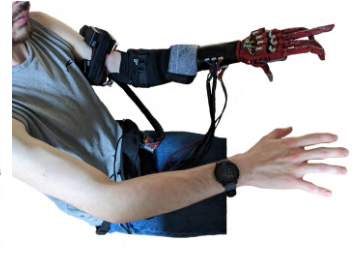
Participant 006



Participant 007



Participant 008



Participant 009



Participant 010

Figure A.1: (Cont.) Experimental setup for each participant with limb difference. Experimental setup for each participant with limb difference for stages 1 and 2 (left), and 3 (right). During stages 1 and 2, participants wore only the electrode armband and haptic feedback armband, while the prosthetic hand was desk-mounted. During stage 3, participants also donned the prosthetic hand. Note that an elastic belt held by the opposing arm to support the prosthesis was used for participants 007 and 010 due to having a short residual limb, and participant 008 due to having partial paralysis of the right arm and shoulder.

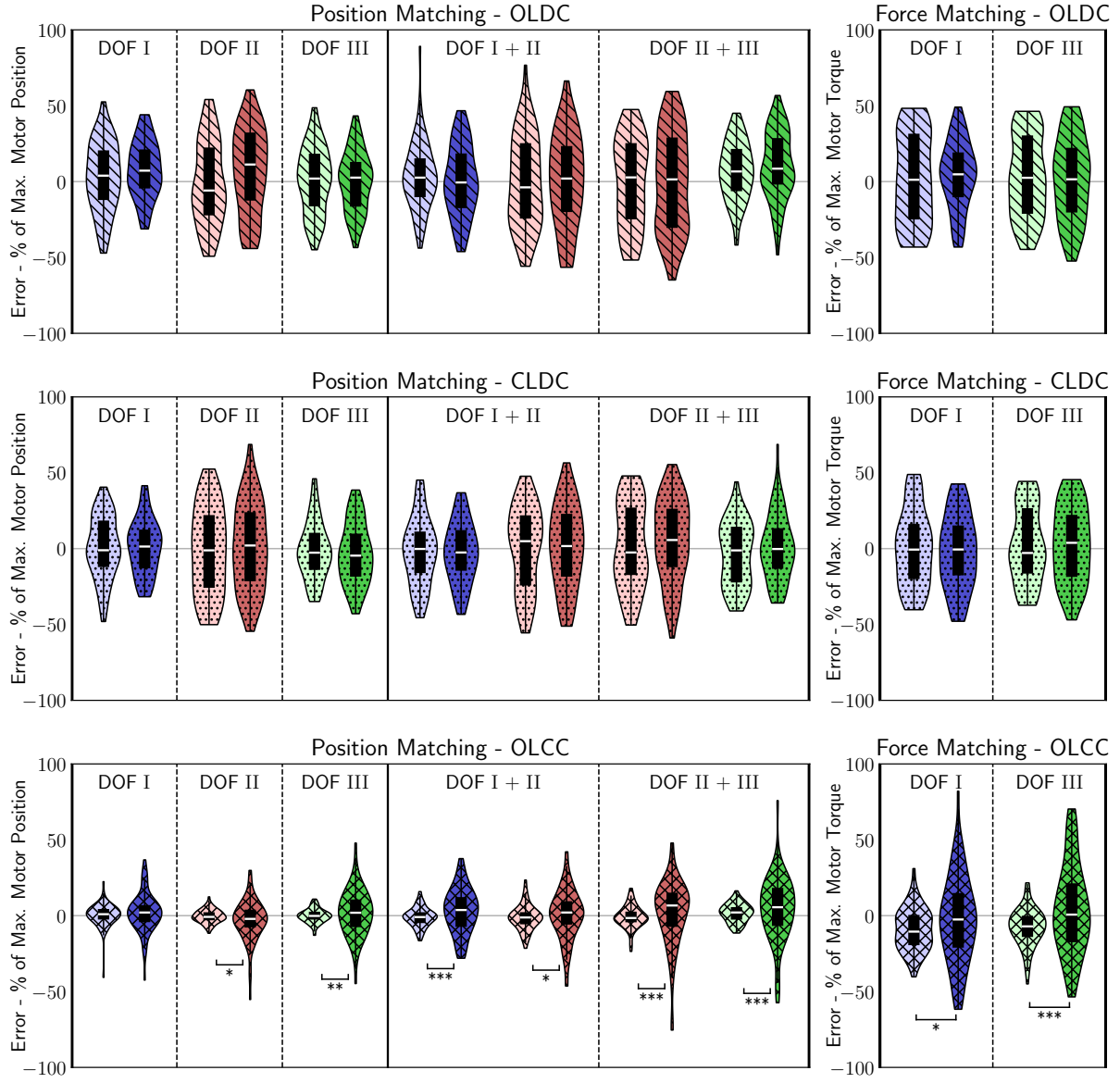


Figure A.2: Matching performance experimental results of groups of participants without limb difference. Participants were asked to match target positions in sets of increasing complexity in terms of the number of degrees of freedom required, then were asked to match target forces with each grasping degree of freedom. Left: Position matching performance of single and dual degree of freedom motions, performed with no prior training starting from 1 degree of freedom motions, working to 2 degree of freedom motions in the order shown. Right: Force matching performance of single degree of freedom grasps. Statistical significance of Kolmogorov-Smirnov tests shown at $*p < 0.05$, $**p < 0.01$, and $***p < 0.005$ levels.

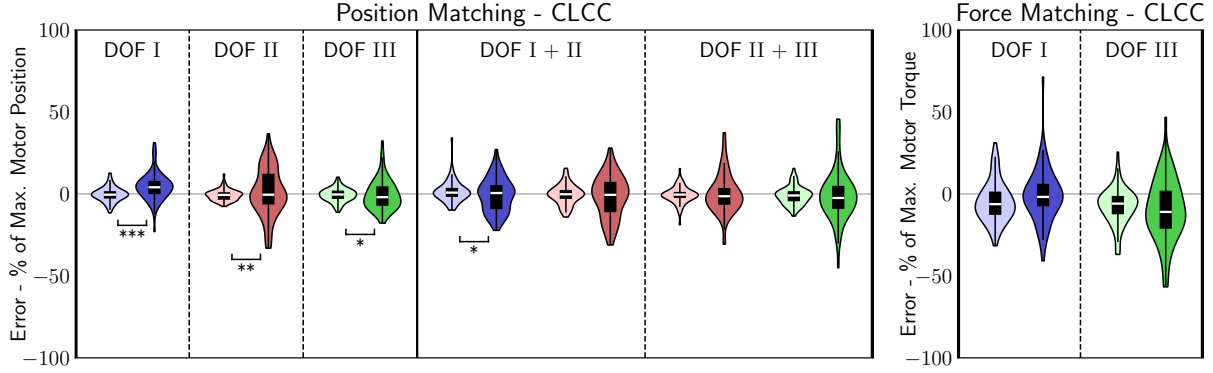


Figure A.2: (Cont.) Matching performance experimental results of groups of participants without limb difference. Participants were asked to match target positions in sets of increasing complexity in terms of the number of degrees of freedom required, then were asked to match target forces with each grasping degree of freedom. Left: Position matching performance of single and dual degree of freedom motions, performed with no prior training starting from 1 degree of freedom motions, working to 2 degree of freedom motions in the order shown. Right: Force matching performance of single degree of freedom grasps. Statistical significance of Kolmogorov-Smirnov tests shown at $*p < 0.05$, $**p < 0.01$, and $***p < 0.005$ levels.

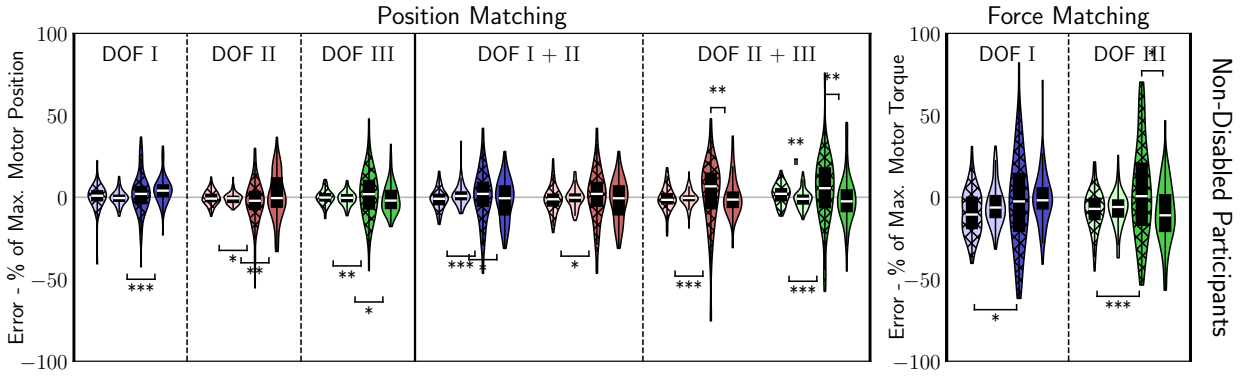


Figure A.3: Matching performance experimental results comparison between the OLCC and CLCC groups. Participants were asked to match target positions in sets of increasing complexity in terms of the number of degrees of freedom required, then were asked to match target forces with each grasping degree of freedom. Left: Position matching performance of single and dual degree of freedom motions, performed with no prior training starting from 1 degree of freedom motions, working to 2 degree of freedom motions in the order shown. Right: Force matching performance of single degree of freedom grasps. Statistical significance of Kolmogorov-Smirnov tests shown at $*p < 0.05$, $**p < 0.01$, and $***p < 0.005$ levels.

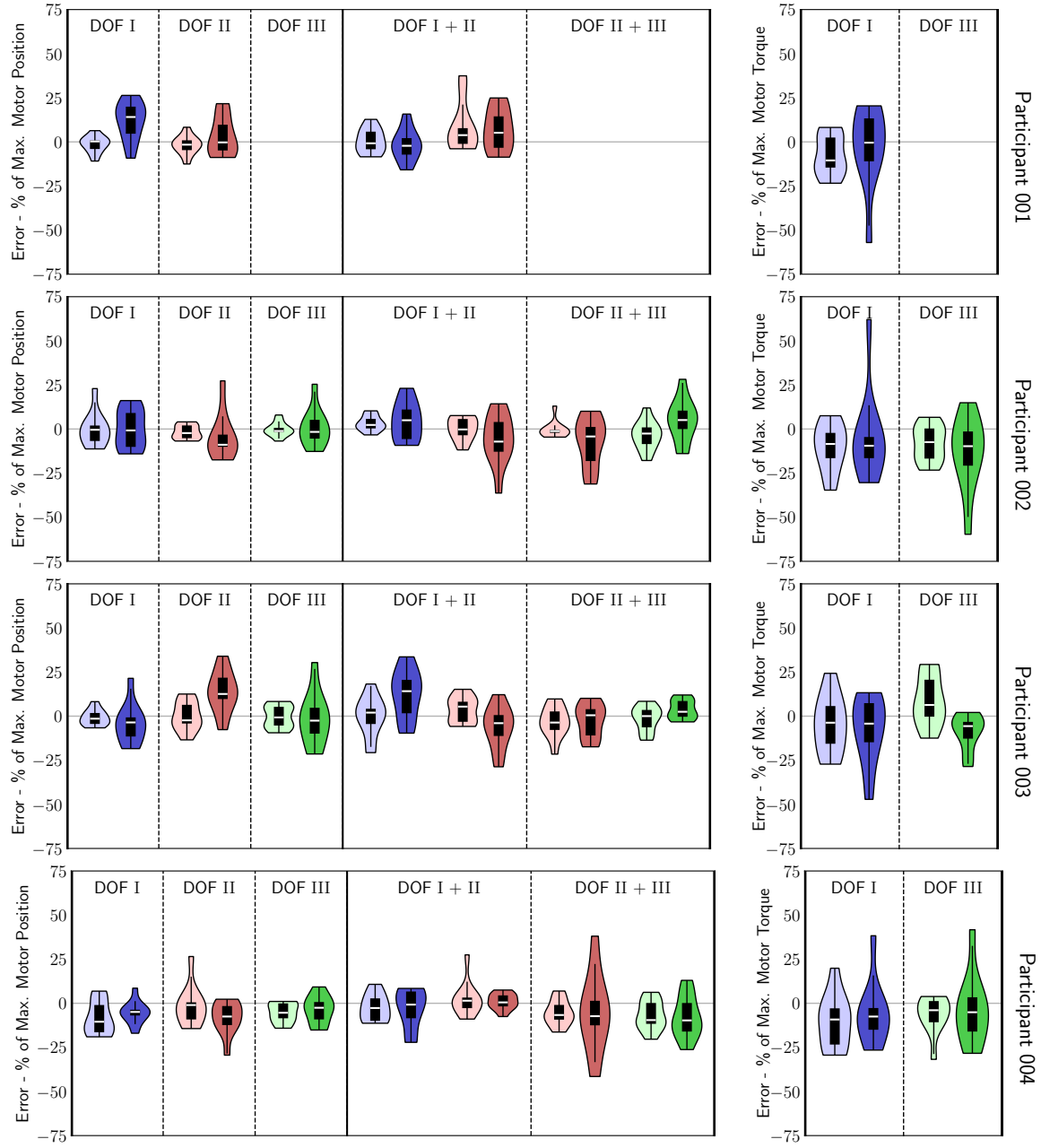


Figure A.4: Matching performance results of participants with limb difference. Participants were asked to match target positions in sets of increasing complexity in terms of the number of degrees of freedom required, then were asked to match target forces with each grasping degree of freedom. Left: Position matching performance of single and dual degree of freedom motions, performed with no prior training starting from 1 degree of freedom motions, working to 2 degree of freedom motions in the order shown. Right: Force matching performance of single degree of freedom grasps. Note: Participants 001 and 005 only controlled DOF 1 and 2 of the prosthetic hand.

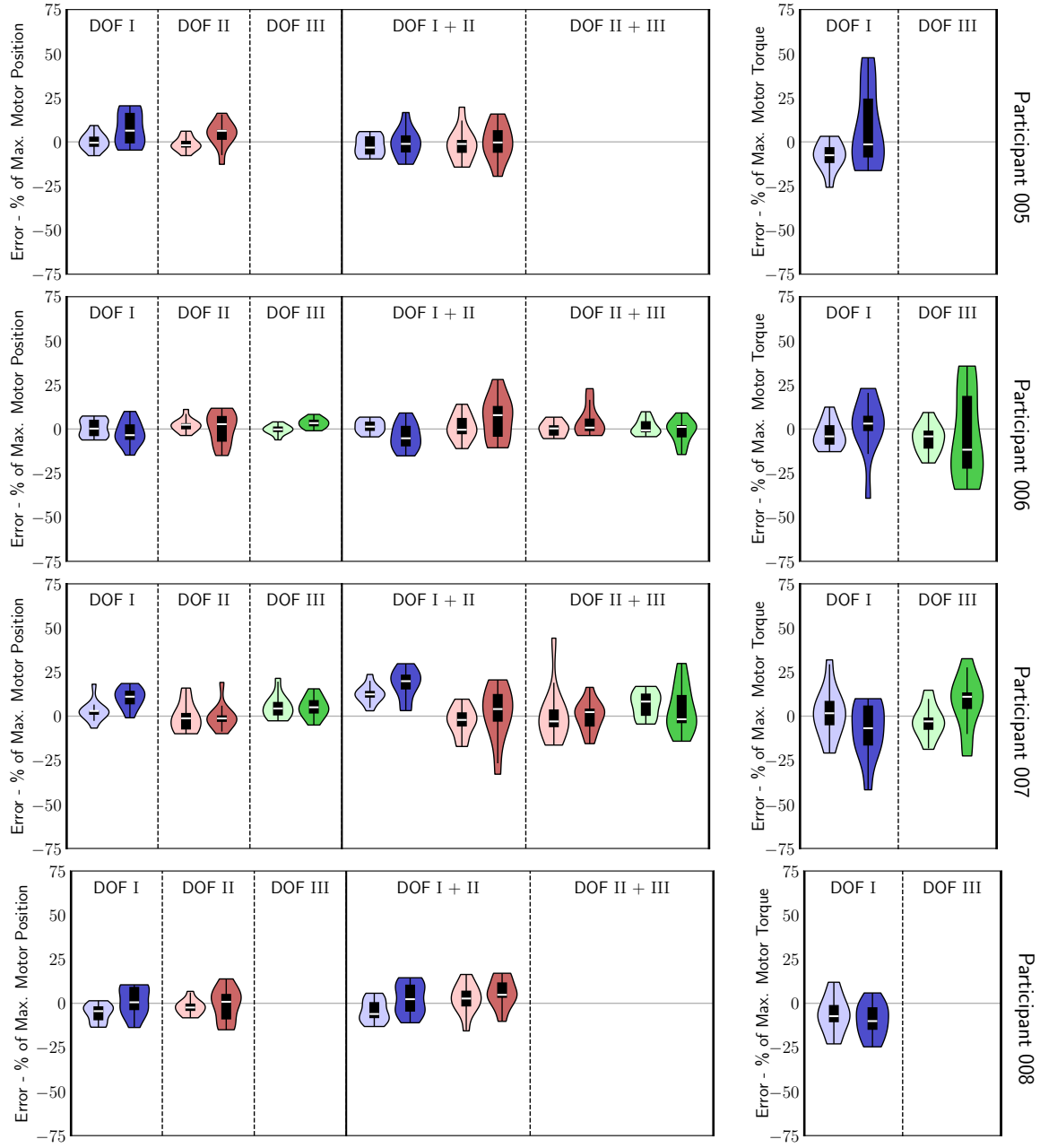


Figure A.4: (Cont.) Matching performance results of participants with limb difference. Participants were asked to match target positions in sets of increasing complexity in terms of the number of degrees of freedom required, then were asked to match target forces with each grasping degree of freedom. Left: Position matching performance of single and dual degree of freedom motions, performed with no prior training starting from 1 degree of freedom motions, working to 2 degree of freedom motions in the order shown. Right: Force matching performance of single degree of freedom grasps. Note: Participants 001 and 005 only controlled DOF 1 and 2 of the prosthetic hand.

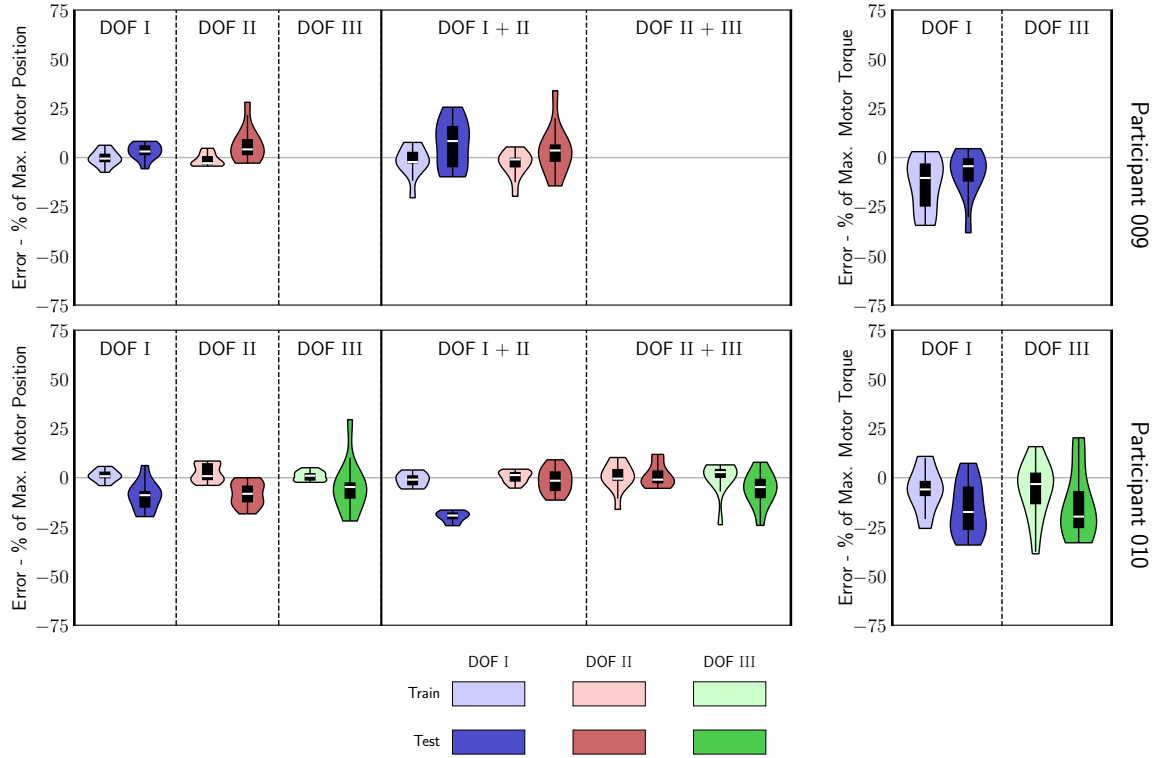


Figure A.4: (Cont.) Matching performance results of participants with limb difference. Participants were asked to match target positions in sets of increasing complexity in terms of the number of degrees of freedom required, then were asked to match target forces with each grasping degree of freedom. Left: Position matching performance of single and dual degree of freedom motions, performed with no prior training starting from 1 degree of freedom motions, working to 2 degree of freedom motions in the order shown. Right: Force matching performance of single degree of freedom grasps. Note: Participants 001 and 005 only controlled DOF 1 and 2 of the prosthetic hand.

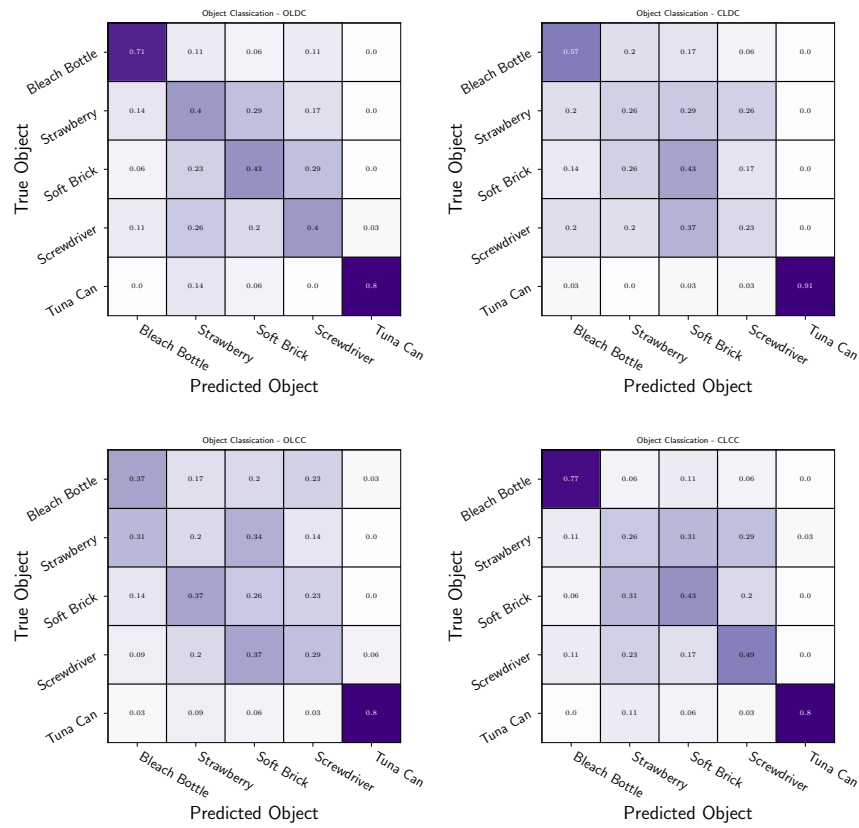


Figure A.5: Object classification results of groups of participants without limb difference. Confusion matrices of groups of participants without limb difference classifying 5 objects from sensory feedback provided by the haptic feedback armband and incidental (audio) feedback.

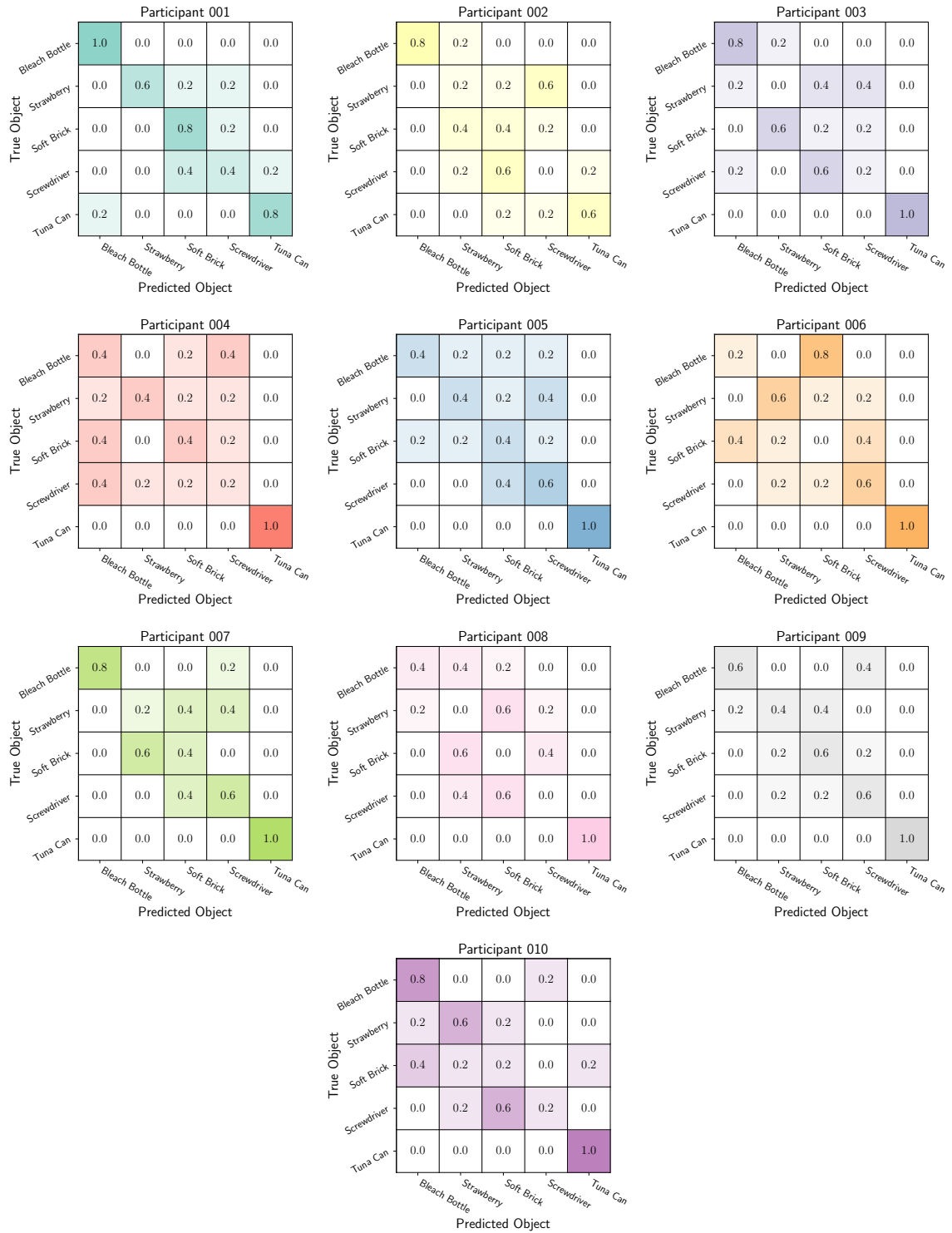


Figure A.6: Object classification results of participants with limb difference. Confusion matrices of participants with limb difference classifying 5 objects from sensory feedback provided by the haptic feedback armband and incidental (audio) feedback.

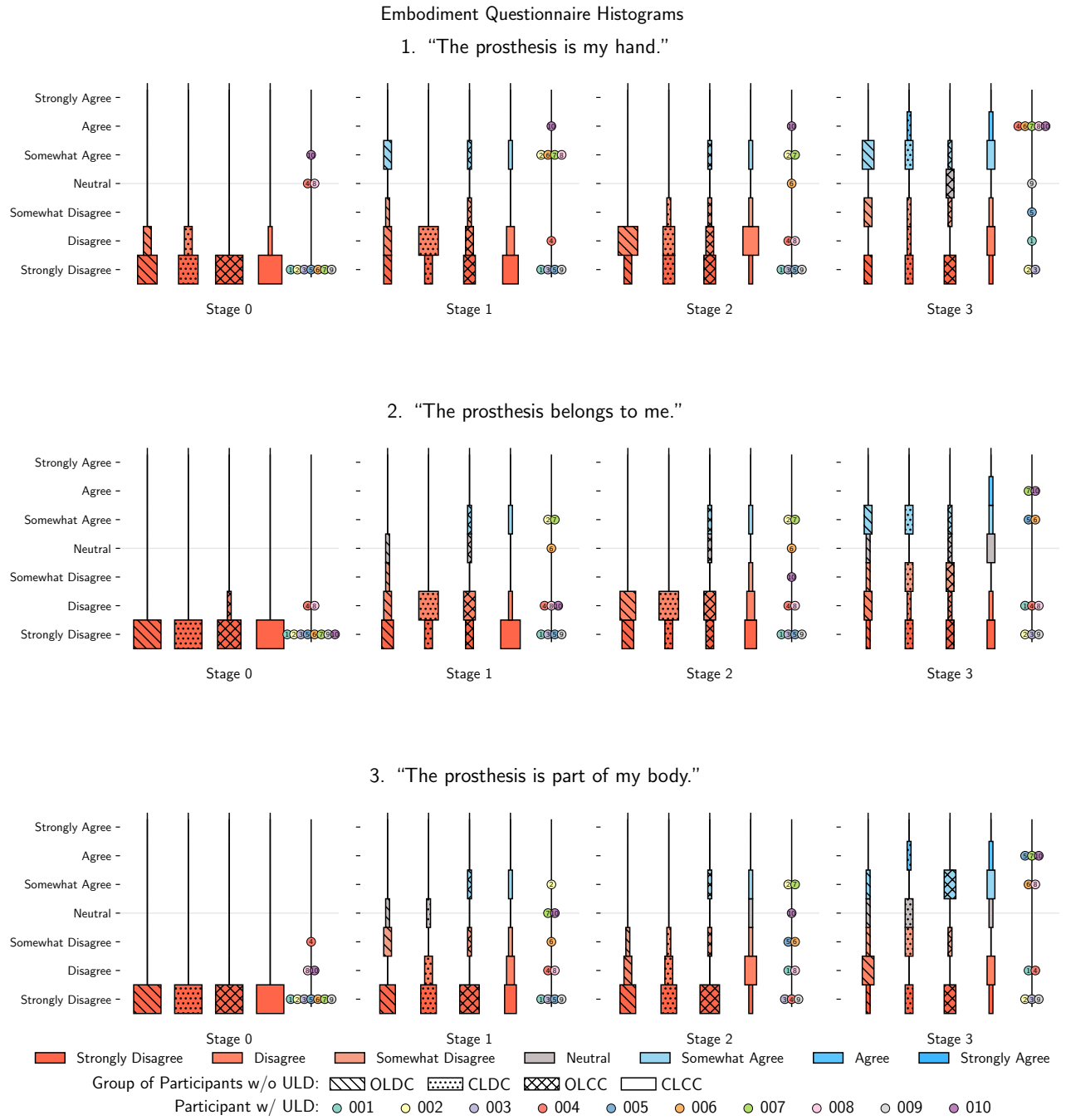


Figure A.7: Prosthetic embodiment results of groups of participants without limb difference and individual participants with limb difference. Responses of groups of participants without limb difference and individual participants with limb difference to prosthetic embodiment questionnaire statements. Results of paired Mann-Whitney U tests are shown at $*p < 0.05$, $**p < 0.01$, and $***p < 0.001$ levels.

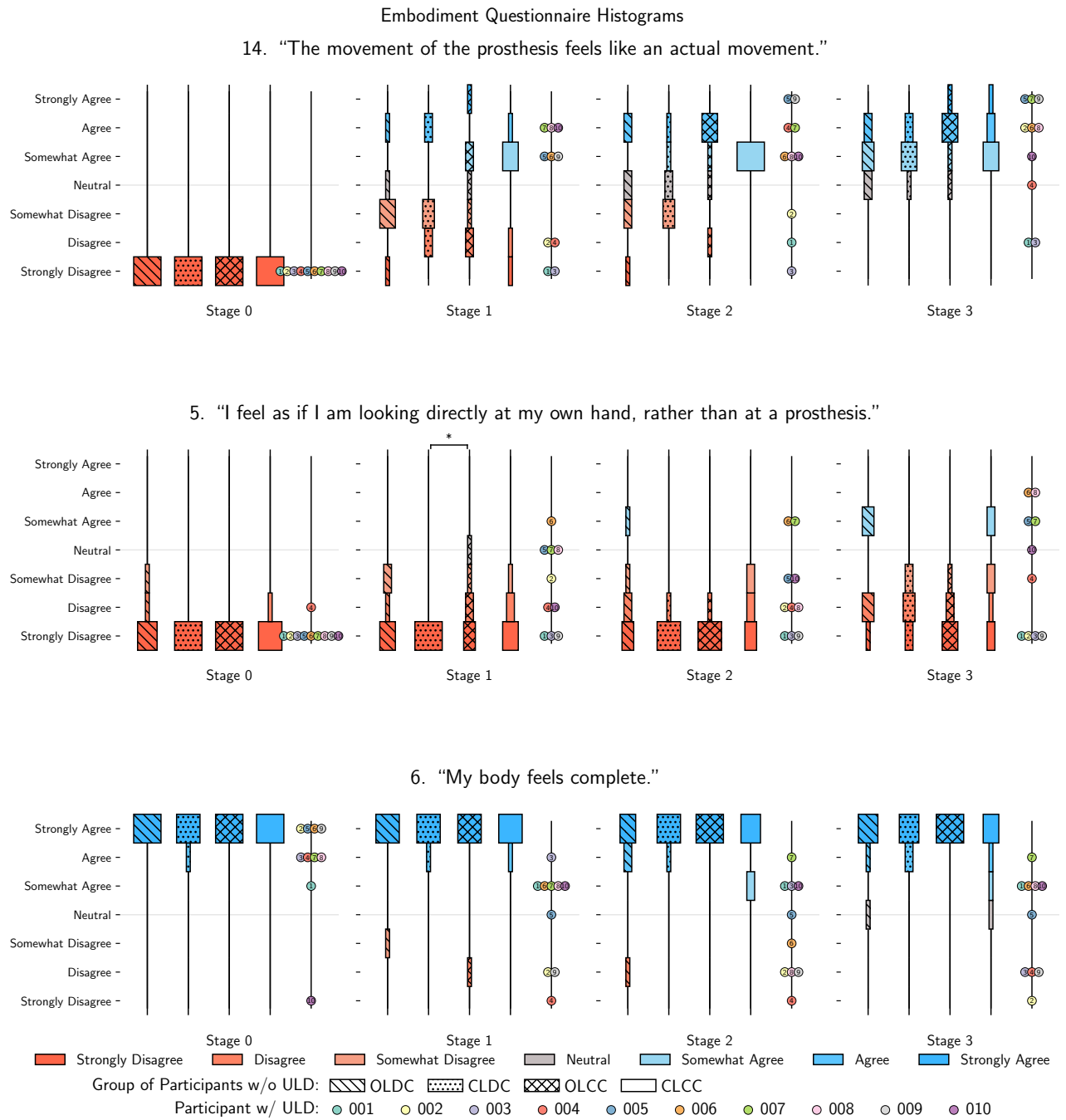


Figure A.7: (Cont.) Prosthetic embodiment results of groups of participants without limb difference and individual participants with limb difference. Responses of groups of participants without limb difference and individual participants with limb difference to prosthetic embodiment questionnaire statements. Results of paired Mann-Whitney U tests are shown at $*p < 0.05$, $**p < 0.01$, and $***p < 0.001$ levels.

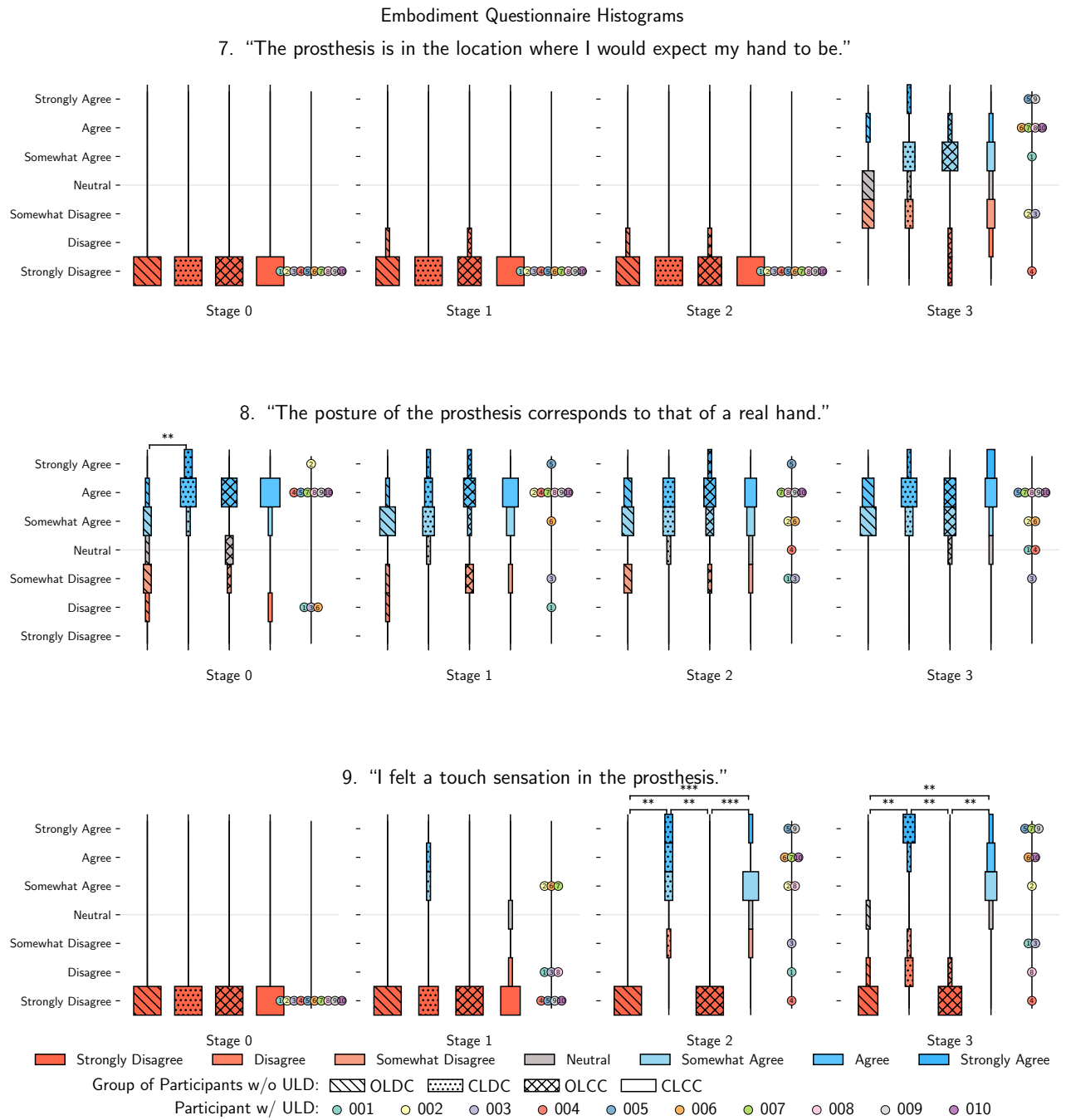


Figure A.7: (Cont.) Prosthetic embodiment results of groups of participants without limb difference and individual participants with limb difference. Responses of groups of participants without limb difference and individual participants with limb difference to prosthetic embodiment questionnaire statements. Results of paired Mann-Whitney U tests are shown at $*p < 0.05$, $**p < 0.01$, and $***p < 0.001$ levels.

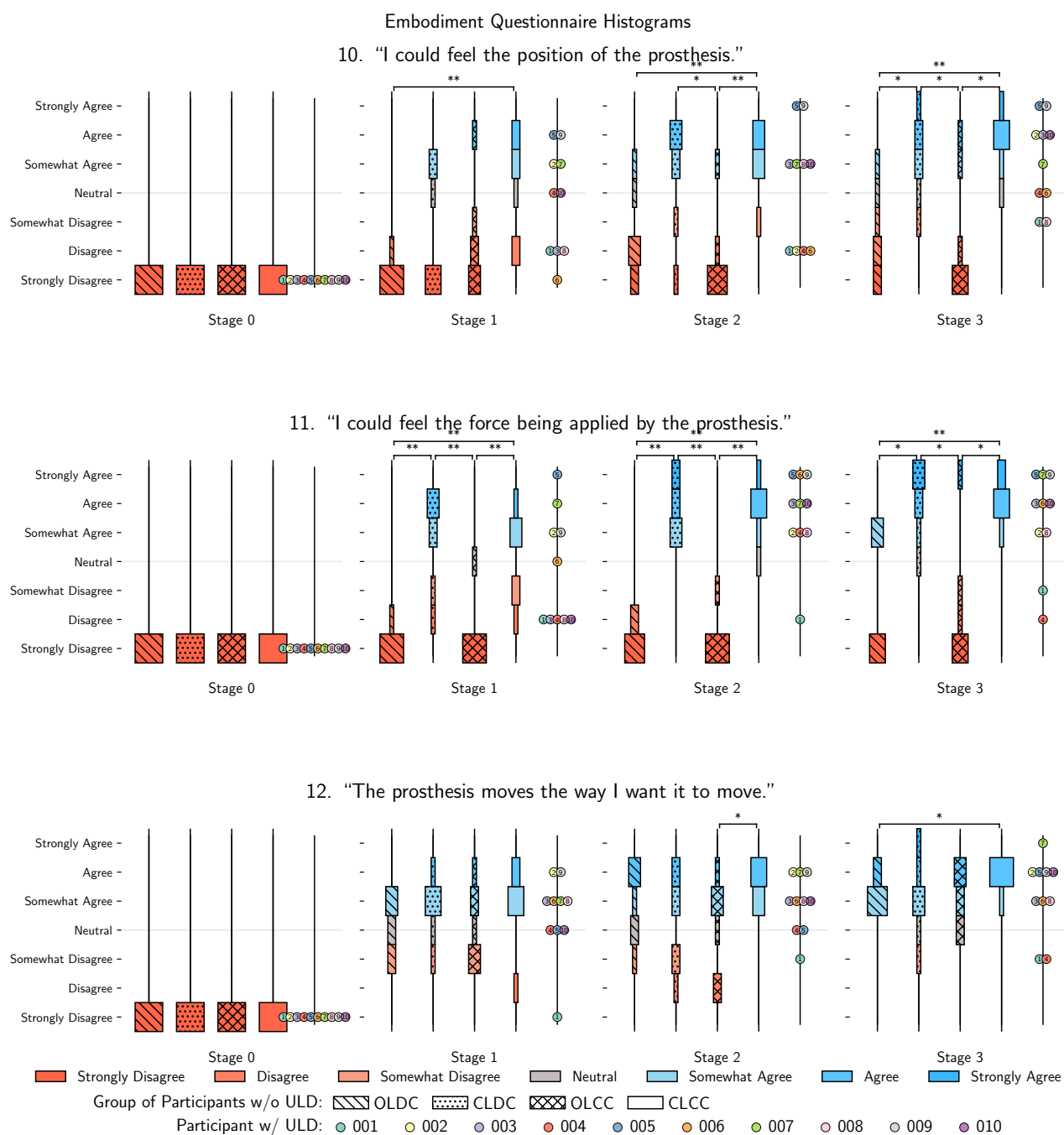


Figure A.7: (Cont.) Prosthetic embodiment results of groups of participants without limb difference and individual participants with limb difference. Responses of groups of participants without limb difference and individual participants with limb difference to prosthetic embodiment questionnaire statements. Results of paired Mann-Whitney U tests are shown at $*p < 0.05$, $**p < 0.01$, and $***p < 0.001$ levels.

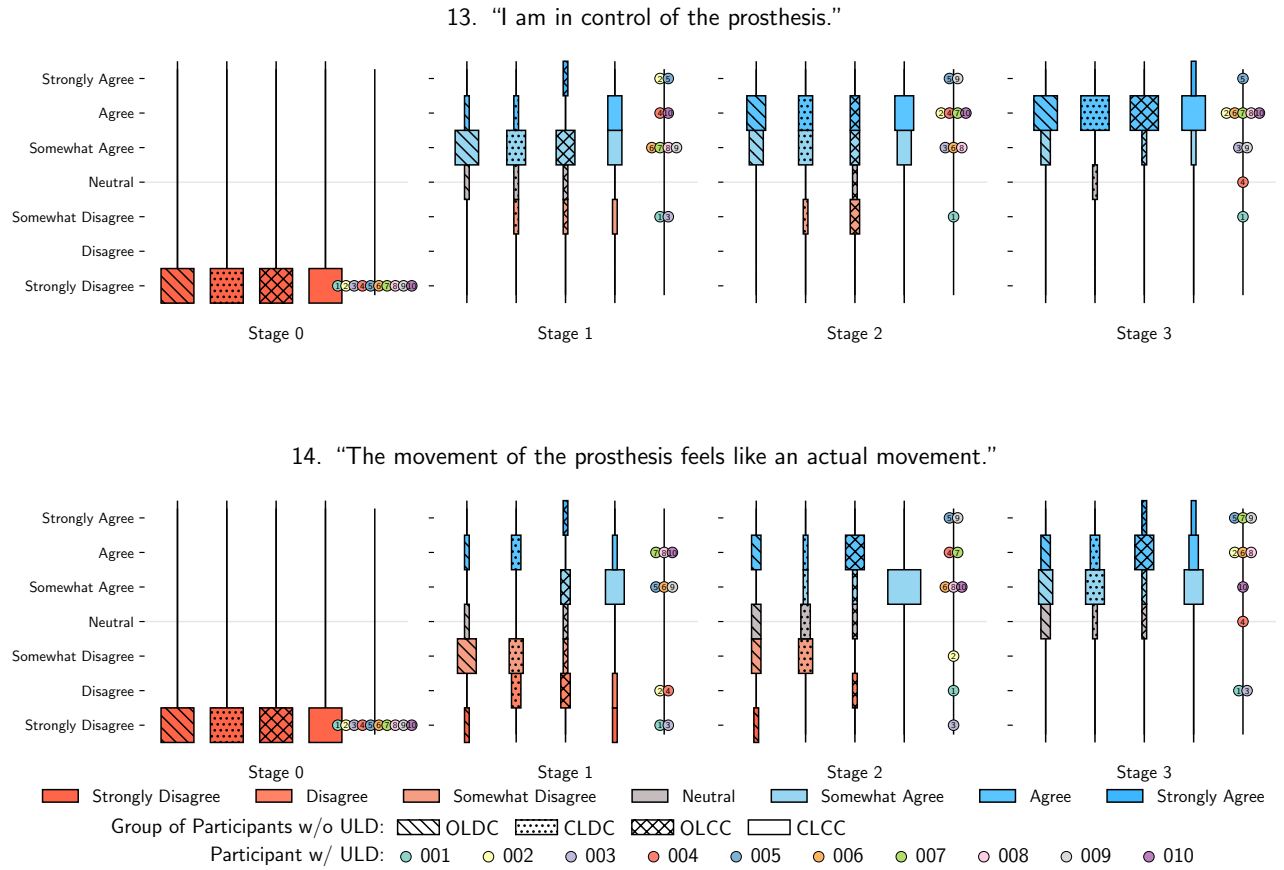


Figure A.7: (Cont.) Prosthetic embodiment results of groups of participants without limb difference and individual participants with limb difference. Responses of groups of participants without limb difference and individual participants with limb difference to prosthetic embodiment questionnaire statements. Results of paired Mann-Whitney U tests are shown at $*p < 0.05$, $**p < 0.01$, and $***p < 0.001$ levels.

A.3 Post-Study Interview Transcripts

In all transcripts, the researcher conducting the interview is denoted ‘R’, and the participant is identified by their participant ID (e.g. participant 005 is identified as 005).

Participant 001

R: I asked you three statements at the start, which were “the prosthesis is my hand”, it “belongs to you” and it’s “part of your body”. So we asked you at the very beginning and he said strongly disagree – that’s expected. You hadn’t started using it and then after stage 1 when you’d used it a bit, you still said strongly disagree. So on stage 2, so after we put the blindfold on you and you had to go and identifying objects and also squeezing onto the can with a target force, you said, we asked you about the prosthesis [being] part of your body, that rose slightly. So that went from a strong disagree to just disagree. I’d like to ask a little bit more about what might have caused that or what you remember from it.

001: OK, I can distinctly remember this point. The way I’d articulate it was I felt after that my brain was starting to work it out. And in a very rudimentary sense, so how the system it had been placed in to operate the arm worked like the ‘rules of the game’, so to speak. And it was although it was never going to feel natural or ergonomic because of the constraints placed by the actual [prosthesis] – the fact it wasn’t fitting correctly to the handle wasn’t fitted at all [on the desk] in [stage 1] and stuff like that. And because it was inherently a bit uncomfortable. My body was starting to work out what movements you needed to do to achieve certain goals, and that for me was a big piece of the puzzle. It’s like almost 1 foot forward about how this system [worked]. My brain no longer saw it as a difficult task that couldn’t be defeated. It was something that I could learn to develop my skills on. There was an avenue to develop that sort of ability and that sort of led in to start that feeling. And about the hand becoming a part of me in the same way that my prosthetics that I use at home now. They, as I developed their roles and their uses and how to use them, the more they feel a part of me. It’s not necessarily the fact that they’re made of plastic or anything like that. I think for me at least, I don’t necessarily see that it’s their usefulness and that was a small part of developing that usefulness. So I could see there could be a use for it, if that makes sense.

R: What it is about a hand being useful that relates it to being part of your body. What do you think it is about that usefulness?

001: In my opinion, it’s a tool – and this might be my outlook in life because I have never had a hand on my right arm. I maybe assign something different, maybe assign a different feeling than I do with [my left] hand. [My left] hand is a part of me. But whereas I forever see anything [on my right] as something that is just an extension; artificial. So I assign value to being a part of

me is how useful that tool is at the end. If that makes sense, it's probably the best way I can articulate. It translates to a feeling of being mine in a way.

R: That that's very interesting, thank you. So [after stage 2], it started to feel like you were working out how this is gonna work. But, on the other two questions, "the prosthesis is my hand" and it "belongs to me" [your response] stayed at strongly disagree. But then after stage 3, when you're wearing the hand, they increased to just disagree instead of strongly disagree.

001: Yeah, I remember feeling when it was on the table, it wasn't on me. I could start to understand the, like I said, the rules of how this worked. Then when it was fixed on me, although it was uncomfortable, it started to feel more like, you know, the best way to describe it is like 'we could do something with this'. We could get a functioning hand out of that if we made those certain changes and that sort of really helped to increase that feeling of like, "yeah, it was a part of me". You know, I could see myself wearing this day-to-day. With the whole feeling and the whole, the whole kit. If it was made more ergonomic I could see that system becoming useful for me. It was the closest thing I've ever had to a feeling of a proper hand being able to work like a proper hand. I've never had that before, I've only ever had hooks or claws. And I know, although the limitations of the hand are fairly limiting, it was nice to get that feeling of being able to, for want of a better term, think and have it happen.

R: So your point of reference for that was having previously tried with hooks and claws that don't look like hands. I'd like to understand a bit more about how the look of the hand affects your sense of it being part of your belonging to you.

001: It's tricky. If you'd asked [me] a couple of years ago, I probably wouldn't have assigned any value to that because I was always very... my arm was a hook back then. Nowadays, especially since I've sort of – this is a bit more history than probably warranted in this interview – gained more of a feeling towards having something that looks like a hand on my [affected] side. So I think yeah, the look of it, I mean aside from the colour obviously, but the like the look of it is important as part of me. I think that's right in terms of like it 'felt' like a hand that had purpose, that had use, and I've not really had that before, mainly because my the hands that look like hands are just cosmetic. They're designed to look like a hand but don't serve any purpose. The only thing I've ever found real use out of was my hook, which obviously looks nothing like [a hand]. I would say that [the hand-like appearance] definitely aided in the feeling towards it being a part of me. It wasn't the main part – that's the use – but the look of it, I could see it. I could see wearing it to work, you know having that one arm instead of having to chop and change [between cosmetic and hook prostheses].

R: The hand you mentioned that looks like a hand – was that a static hand?

001: Yeah, I've had a fair number of limbs. I've had primarily cosmetic prosthetic hands that look very similar to normal hands. I've had one [myoelectric] hand, which is a hand, but it's just a claw like that [gestures a claw grasping motion]. So that was very short lived. It was very heavy. It was very cumbersome. And then I've had mainly hooks which open like that [gestures a split-hook action]. I could see myself gaining the most [out of a hand] with the use that I get out of the hooks but an entity that looks like a hand, so I'd be able to just operate normally with it. I think as I've come a bit older, looks have become more important to me and in certain ways, but not it's not vanity or worried about looking about what how other people look, it's just more for... You know, it's just, I don't know. I don't really know what it is. It's just something I feel more comfortable with. Just looking a bit more normal.

R: So there's this interesting relationship where your priority is that it has a purpose, and then it's extra nice if it also looks how you like it to look?

001: Yeah. And I think that for me will always be right, because I've always seen anything beyond my [residual limb] as a tool. It's serving a purpose, be it making my life easier bit, its ability to take up less concentration in order to achieve its objectives in the same way. You don't need to apply all your concentration to pick something up, as you know where it is. And I think that's the way, especially when we were doing the hand stuff to work out what bits were, I started to feel like my brain could learn this. It could pick it up and it would be able to offload some of the more concentration focused tasks around like how or what object I'm picking up or something like that. That's, that's why. And then on a secondary point, yes, you're right, the look of it.

R: The next statement I'll ask about is "the posture of the prosthesis corresponds to that of a real hand". Initially you said disagree, and then after stage 1, you also said disagree. After matching positions after stage 2, which is the blindfolded one and the grabbing hold of the can it went up to somewhat disagree, and then after wearing the prosthetic hand and doing tasks with it [in stage 3], you said neutral.

001: Yep, seeing how it moved in terms of just the basic tasks and helped develop that. I think wearing it was the real thing and I and I think again this probably plays into the fact that I just had five fingers working to achieve a grip and not only that, but I had five fingers working with a degree of information coming back from said fingers. I've never had that before, especially from a hand like structure. So that's probably why the rating went up there in terms of you look at it to begin with, it's not attached to your body. It moves in quite a like an automated way. And then the more I picked it up, the smoother it moved, the more I could get it to do what I wanted it to do and that sort of fed back into the fact that this can move like a hand if I can learn how to do it. Plus, the information coming back to me around the sort of grip strength on them was useful. It gives you more information than, say, a blank prosthesis would, and I think

that's probably why that went up in terms of the look and the feel of the arm.

R: There was this question, "the prosthesis moves the way you want it to move". After the first, so at the beginning, it was strongly disagree because you haven't done anything yet. So after position matching [stage 1], also strongly disagree, and then after stage 2 with the blindfold and stage 3, they were both somewhat disagree. It might be asking you to repeat some of things you already said, but why do you think like this?

001: Like I mentioned earlier, it was the feeling of getting the hang of it. I'm being honest, it probably plateaued because my ability to concentrate on getting the hang of it, my energy level, came down below the line of actually being able to learn, so they probably passed each other probably midway through the [study] and my sort of ability to learn was starting to wane, but risen initially because I felt that there was a possibility for progress here. It wasn't an insurmountable task. So that's why that feeling developed [which] is like "I can get it to do what I want". I just need to focus on it and that sort of stuff. And I definitely felt that if I continue to do it maybe with a fresh head, I would have continued to get better at it.

R: Understood. So like a longer term over, say, a couple of days or a couple of weeks?

001: Yeah, with a more ergonomic design, definitely. I feel like I'm bashing on the design. I do know it's a prototype.

R: No, please don't apologise. I need to ask more about that ergonomic design. What do you mean by this?

001: I mean in a perfect world, I'd like one tailor fitted to the to my little arm. I know that's not feasible, but. The sensor band wasn't too bad. I think that was by far the best part of it, and I understand that's more me and the constraints of what we had to work with in terms of muscles and where it was best fitting. I think as well the blocky force feedback [armband]. Not only was it uncomfortable, but it was very it was just it was big and numb. I think if that was obviously a lot smaller, I understand the difficulty in building these sort of things, but if that was a lot smaller and a lot lighter and less lag generally as well. If those changes could be made, I think you'd be starting to see a fair few higher scores on those. Does it feel like your arm, can you get to do what you can do? I said it would be easier, especially with the lag, it would be easy for the brain to pick up what was happening.

R: It's good to have this noted, down from someone who's used it as opposed to just [a researcher's] view of it. I'm going to ask you about your perceived performance in each of the tasks. For position matching you had that down as 50 out of 100. For the second one, which was the blindfold one, you also put that down as 50 out of 100, so. For the final one, where you wore the arm and you did the task it was at 35. So I'd like to know your thoughts on that.

001: So 50 out of 100 for the first, and second. I remember the position matching one. I was really sort of happy with the fact that I could get it to [move] there. I felt after we've done a bit of that bit of that position matching, I felt, like I've said, I understood how the thing worked in terms, but it was very rudimentary. And then the blindfolding one, was the first time my brain had to literally like literally interpret the force feedback and I didn't really understand it enough to comprehend to fully sort of feel confident and be able to do that. I didn't think the movement was a problem. Apart from the sort of the actual mechanics of it that we were having difficulty with, like you know, slipping off the arm and stuff like that, but it was more the ability to understand what I was feeling. I hadn't had enough time with it to... it was very, very broad strokes in terms of the force we, but I still felt that I could still understand and get it to do what I wanted to do. I think towards the end where I was where it was mounted to me that it was limited by the mounting of it, and the I think tiredness when it comes to executing what I was trying to achieve basically. The core components are there in terms of like what [the controller was] trying to, what you were trying to achieve with that arm. It's just the design and the ergonomics and spreading out the learning with it. You'd get there. I feel definitely the actual the brain can do the rest. I felt if you take anything away, I felt that I could get there with enough time and enough perseverance with it. I felt that the force feedback and the information was there, I just needed time for my brain to learn and interpret it, and the energy too. I mean, that was something I could have done a bit better with in terms of taking a few more breaks instead of just pressing through it.

R: I'm gonna ask you about frustration while using the prosthetic hand. So, for stage 1 so the position matching you said 55, after stage 2 you said 50, so that was after the blindfold and the objects, and then after stage 3 it went down to 30. What do you reckon was going on?

001: Frustration feeds back in for me personally; I would have gotten more and more frustrated if I felt I couldn't learn a system. But because that wasn't the case, because I felt like I was making some progress, the frustration went down. Especially towards the end when I had that success with the [stacking checkers] and the moving the objects and stuff like that, I felt like I could get this to do what I wanted to do. I was starting to understand and comprehend how it could work. And not only that, but how it could be useful to me. And that that's why that frustration level was going down. It started off slow, I think. Over the middle period I felt a bit frustrated by the fact that I was trying to understand the force feedback and pick up what it was trying to tell me and interpret it, which is probably why you don't see a [decrease in frustration].

R: The nature of the third stage is that you have these tasks in front of you and it's quite tangible and you can see how you're doing on the task.

001: Yeah, and that probably did play a role in it. Having an objective and achieving that objective

using the arm feels good. With not as much expected difficulty. I thought [I was going to] struggle a lot on some of those tasks and it wasn't as hard as I thought it was gonna be. I don't know whether that was necessarily, uh me having spent more time with it up to that point, whether it was because, you know, the force feedback or whether it was just because I just managed to get it in a good position when I closed it. It's probably a mixture of all three. But yeah, generally it's being able to see a task and complete it without as much difficulty as one would initially expect. I would still find it easier to achieve those tasks with my hook than the arm, but obviously that's because the hook fits me a lot better. It's a lot lighter. Although it doesn't give me as much feedback in terms of the [cable], I'm much more akin to what the tension and the wire that would connect my shoulder to the actual hook. I've got more [learned] information around how that feels and what it means. And I think that could all happen with enough time. With the arm, the only difference is time. I've spent years using a hook, so I've spent years to fine tune in the same way you spent your entire life understanding what your hand is telling you. For me, my body just interprets the tension in the wire to how open they will close the hook is, and the same could be said about the position of the pads on your upper arm. In terms of the force feedback, the information's there. It's just the time it takes to develop that understanding of it, and I think the key for that frustration is my brain could see that path of understanding it. It could make sense of it, "I'm not there yet, but I can work on this". If you gave me enough time and enough exposure with it. It was probably aided in the fact that I went in thinking it was gonna be really difficult – and it was – but it wasn't anywhere near as difficult to pick up as I thought it would be.

R: I would like to ask is there anything that we haven't talked about yet that you'd like to bring up?

001: Not really. I think it's the implementation for me at least. It was a challenge in terms of the discomfort [the haptic feedback armband] was causing on the skin [of the upper arm]. There were no, like lasting effects of it. It was just mild discomfort at the time as it was rubbing against the scar point [on the upper arm]. Also having a proper stand so that the person doesn't have to load bear the whole [prosthesis]. I know we have the strap which worked really well that took a lot of the weight off my arm and allowed me to focus on the task was very useful definitely.

Participant 002

R: There was this question which was the “prosthesis is my hand”. After we got you to match the positions [and forces] and then also identify objects with the blindfold on. You said, you somewhat agree, but then after you wore it and did the pick and place tasks you said you strongly disagree. So, I want to understand a little bit more about that and get your thoughts on it.

002: Right, visually what I find is with a lot of prostheses they don’t actually give you a hand that looks like a hand. As a replica, if you took away the skin, I would say [the prosthesis used in the study] would resemble [a real hand]. The fingers of a normal, everyday functioning hand so visually there you can [imagine] that as being part of your hand. Right, but when using it you realise how disconnected you are from it. You quick you very, very quickly realise that. It doesn’t move the way that you want it, it feels like an appendage on [the end of] what you are used to now. And in my personal opinion, that comes before the actual using of the [prosthesis]. You have to very strongly think of how to use the [prosthesis].

R: I’m really interested in the bit where you said where you put it on, and it becomes like an appendage.

002: I personally, and mentally, cut my hand off my arm when I knew it was getting cut off. It was dead to me. I quickly got very used to the idea that my arm was no longer there. I’m lucky enough never to have received or had phantom pains that I am aware of. Now if I have, I’ve not took them as phantom pains; I have took them as just everyday living with my condition or my situation. You get used to having nothing there, so when you put something on your arm where you’ve been cut or amputated to. If you actually think that that there is your hand, even though you can’t open it and stuff like that, but when you put something onto that, it’s like you grabbing hold of the stay of the brush and holding it out and you can feel that your arm wants to go down. If you went into your kitchen and there was a long sweeping brush and you picked it up and you held it by the handle and lifted it. It would naturally [go down] because gravity pushes it down. So that is what a prosthetic arm feels like. So do you remember when I said to you right at the beginning [of the study] that you will never get a prosthesis working correctly, because the first thing that you need to do is make sure that that prosthesis feels a part of that person.

R: So would you say that the way that it feels like it’s part of you is a lot about how it’s sort of connected or attached to your arm?

002: Yes, and I also think that the sooner that you can get an amputee a prosthesis the better. But, I also think that surgeons need to understand [that], when removing a limb, where is the best place for that person? Like think not in that moment but think a week [ahead]. When this

person does have a prosthesis, if I cut it off here, is it going to help or is it going to more hinder that person with the prosthesis? So if I'm able to cut there, that would give them a better chance of using a prosthesis, which would give them a better quality [of use]. You get what I mean?

R: I remember at the time you said that there was something about the way it felt with the socket and it wasn't quite rigid.

002: Yeah, you mean the one that you've got?

R: Yeah, the canvas or fabric socket.

002: Yes because it was strapped to me round once. I mean that [socket] is the test piece so it would be very difficult for you to literally it or physically make the [socket] per person, for everybody.

R: What I would like to understand is that when it was mounted on the desk, and it wasn't attached to you, you said that you somewhat agree that it is "part of your body" and that it "belongs to you".

002: Basically, I think it's because being an amputee you hold hope. I think that's the only word you could use really is "hope" that the prosthetic limb that is there, designed for you, will work. Because I know now being nearly six years down the line [since amputation] that it is very difficult for people to make a prosthesis as an upper limb, because of the complexity; the movement of the fingers and the hands. Now, until – from my personal point of view – these little motors become a lot stronger, then you're limited to what you can use that prosthesis for. So when you look at [the prosthesis used in the study] that you made. A blind man touching that would be able to say that is a hand and they will be able to know that then fingers physically bend and move. Whereas the old prostheses, they made them to look like there was a proper hand visually; from a distance they look like a hand, but a hand that doesn't move. Whereas [the prosthesis used in the study], you can clearly see that the fingers do move independently – and that's it. So that's why, when it's on the table, you can see it's a hand and you can relate to that as being your hand – not that that is your hand – but you can relate to that with the hope that it will work and you will gel with it.

R: So when it's on the table a lot of this is how it how it moves and how it how it looks?

002: Yeah.

R: Until you actually wear it and then something changes?

002: Yeah. It's like there's like a line that you can't go across, because there's no connection with [it]. Now, I'm assuming, or I'm thinking, that if something, if the sensors were better and they were more adapted to the physical movement of your arm when using the prosthesis, then you will probably feel more in tune with that. There's lots of different elements. [There are] far more

elements to a person being able to use a prosthesis as a robotic arm. Whereas a lower limb, you are connected with it straight away. Even though it feels funny at first because it's just there and it does only two things, it bends at the knees, bends at the ankle. Or maybe three things: it keeps you upright [as well]. If your balance is fine, it doesn't get asked for anything more. When [more] things are asked for you then have the blades and other implements that are specially designed. There isn't that yet with an upper limb. The strapping [of an upper limb socket] to you restricts your movement. It also, unless you've got the correct or a decent, like with me, [longer residual] limb, lower below elbow then you can't. There isn't the structure there to [give] stability. So, because the stability is not there and a lot of the weight is on the end, it will naturally gravitate to dropping down. See, I do think even though I've never actually looked into one of these "robotic ones" that they have. It might be worth being able to see how they have the sensors because [those hands] seem to be [performing] quite well. My experience other than saying "***** *****" is that they do the bare minimum for people [in the UK health system] and it's absolutely wrong. So, I mean this is a [comparison] scenario, a lady that I knew that had her leg amputated at the same time I had my arm. The three-year period she had. Extreme physiotherapy She had [multiple prosthetic] legs. She was then given this thing called a C-leg, which costs money. I roughly estimated, conservatively, probably about £100,000 [including] physiotherapy, legs, and the C-leg. I was told that the Ottobock Griever arm was the latest technology. Now I never gelled with it because it when I moved my arm, it sent different signals, so I couldn't control the signal by using my arm. Plus there is quite a bit of weight on the end where your hand is because you haven't got [a limb] from your elbow to the wrist, that structural strength [is gone]. So I was watching this [movie] set in the 70s. And they go into this hospital where they show this robotic arm and there it is the Griever. It's literally there, so it's a 1970s product still being used in the 21st century. 50 years down the line. We were told by the people at [the hospital] that there isn't as much money into upper limb because people do not use them like they do the leg. Well, that's a catch 22. If there was more investment, it would be better. These people that are using the Hero arms, they're using them. They must be getting made out of some something that is making them light weight. It could be the fact that my arm, because I've only got like 4 inches below the elbow. If I had 5 inches maybe? That would help. Or 6 inches. I don't know, but this is why I'm saying. I think surgeons need to be [thinking about] afterwards when people do come to need these prostheses. So for them to know that if you cut it rather than there do it at above the elbow then that helps.

R: You were mentioning a lot about rehabilitation [for] people who've lost their leg. How do you feel about rehabilitation for people who've lost an arm?

002: Right, my experience from even when I had the cancer. I was just left to fend for myself and

my arm was amputated. I was told I was part of this family now and I could phone [the rehabilitation center], contact [them] anytime. Very shortly after it was made clear that myself and other people, if we had problems, we had to go to see our doctor not [them]. I went to [the rehabilitation center] the attitude of the consultant that I saw... [he] was an old consultant. And he was very, very old fashioned. I'm very liberal and I say a lot of things, but I was very surprised by a couple of the comments and the actual process that the consultant came out with then. When I actually went to see the guy who was making the prostheses, he was part time because he was retiring and it didn't feel that my needs were being listened to. It was "this is what you get – deal with it", which frustrated me a lot more because it felt like [that] every time I went to [the center]. I then asked the hospital in [a second location] to see if they could contact [the second rehabilitation center] for them to take me over because of the way [the rehabilitation center] was being. I don't think they were being naturally rude or anything, but I expected a lot better than what I was getting because I think that being an upper limb [amputee], I needed [better] and I didn't feel that I was getting it. I think basically the best way of describing my very first [prosthesis] was. It was that big and funnily shaped that if a coach load of people lads was going down the motorway you could have quite easily and put it on the side of the motorway and used it as a portable urinal. That's how it felt and looked to me, and once I thought about, I couldn't get that out of my mind. Because it just wasn't... I was disconnected with it. There was no connection between that prosthesis and me in any way, shape, or form. Then being in [the second rehabilitation center], there was a young guy and he was very good and he was full of hope. I asked after a while for these robotic arms because I was in England and I lived in Wales. I had to then go back to [the rehabilitation center], because that was my country that I lived in so I couldn't really cross the border. As much as they helped me as much as they could, after a bit, when I wanted actual big money [for a more sophisticated prosthesis], [then I had to be] dealt with through [the rehabilitation center]. When I did go back [to the rehabilitation center] they were quite apologetic, but I was full of hope. I was full of hope, and what was said to my face [reinforced this feeling]. Soon as I went out the door, it felt like, "well, he's not getting that, he'll get what he's given". As much as I tried to work with [the rehabilitation center], I was taking time out of work to go there, so I was losing money. It was costing me money and the actual arm was just no... it wasn't any good.

R: Can I ask you about another one of the other questions I asked you [during the study]? The statement was "my body feels complete".

002: I'm happy with the way that I look and I'm happy with not having my [hand]. Yeah, that it doesn't affect me.

R: So, before we started you said strongly agree. Then what we found was that when we started the

experiments, your response went down to disagree. By the end [of the study] it was strongly disagree.

002: Obviously when you're doing these trials, or you're dealing with prostheses it comes very quickly back to you that you have lost an appendage. You quickly then revert back to knowing that you've not got that hand. I don't ever think twice about doing anything with my arm because I'm so used to it not being there now. My end of my stump, I class that as my "grip", if you know what I mean? So I use that for carrying things and stuff like that. When you come to do [tasks] with a prosthetic arm you quickly realise that it's not there. It quickly comes back that you do have this [limb difference]. But I do find that, in my case, prosthetic arms made me more disabled, because they do not benefit me. I've never had anything that [does benefit me] because the ones that I have had have never gelled or helped me. Going back to the same thing; to me to make sure that these hands will [gel], it has to feel natural to you. And is it? If it doesn't feel part of me, it's always going to feel strange. I've never experienced a [multi-articulating hand]. I did go looking about for them because there is a place nearby and they do robotic arms there. They said to me that "you're looking at thousands and thousands and thousands of pounds for them". If it knew it would work and it would enhance my life. I'm not asking for it to do a lot. I'm asking for it to be able to grab a can of coke and be able to have a drink. Or the best way I used to put it is to give my right arm a bit of respite. Because my right arm is constantly doing everything. If I had [a prosthesis] and I could rely on it on sometimes then [my right arm] would get respite.

R: The amount of frustration you experienced, after the blindfolded stage, you said your frustration was 100%.

002: Yeah, because you've got no feeling. You can't mentally visualise what you've got in your hand or across. There's no connection; you could have put a leaf in that hand. Or you could have put a screwdriver in it. I would know what it was until I visually saw it.

R: I need to poke a little bit more at this one to understand. What is it about not having this connection that made it frustrating?

002: There's no feeling. Like I said, I could have a screwdriver in my hand. I wouldn't know. With my right hand, I have sensitivity so I can tell, or I can relate with seeing something and the touch... it relates. It stimulates your brain to know what it is. Because there's no touch, or no stimulation, my brain is just blank. I mean, it's like now I can touch something with my right arm and my left arm, and I know I'm touching something. I know if it's hot, I know if it's cold. If I had my eyes closed, I could hazard a guess, because if it was a ball, I could feel around it if it was some kind of shape, I would be able to tell you possibly what the shape was not as well as my hand. Because of the dexterity [in my hand] and the amount of nerves that's in there

to let, you feel what you're touching. With the [residual limb], I'll get some sensation, but not a lot. A prosthetic arm, the way that they are at the moment, you have to visually see what you're touching to know what it is. I don't think you will really ever gain the stimulation with a robotic arm. Unless it's permanently [integrated with] your nerves. So to me, the only way that things like that would be able to work is... with similar things that you're doing with the vibration [feedback]. I don't think you'll ever get the actual feeling of the proper arm because [it's too complex] and stuff and you couldn't put my [hand] in [the prosthesis].

R: One final question: is there anything that we haven't talked about yet that you would like to talk about?

002: One of the big things I think is that the little motors that you require to move the fingers independently [based on] your muscle movement or your sensors. They need to be lightweight as possible, with as much power as possible, because if they haven't got the power then you can't grip a can of coke. So if you can't grip the kind of coke to drink, then it's all in that motor. I think what we all need to understand is that a prosthetic arm. It's all when you go to these [rehabilitation centers], they measure your right arm or your left arm and they make an arm the same length. With a prosthetic arm it doesn't work because when drinking a can of coke, yes, you bend at the elbow, [but you] bend at the wrist as well so you possibly pull away 3-4 inches. It can't physically work, if it's still made the same length as a proper arm. Because with a can of coke then what happens is, if you don't flex the wrist, you have to physically move your arm in a different position.

R: You have to bring your elbow up.

002: It was just reminded of when I got my Ottobock arm and I tried using it. I was doing little different tasks in the house and I decided that what I was going to try and use this hand as best as I could. One particular day [I decided] I'm going to put the curtain rail up in the bedroom. I got it all prepared, and goto hold the bracket so I could drill so I could mount the holes in the wall. As I flexed my arm it threw off a separate signal, because my your arm was in a [different] position, it suddenly started spinning that thing around. And I couldn't control it because the sensor in my arm was or the muscle in my arm was touching a different part of the sensor which was giving it a different signal? So obviously it got launched and never was worn again.

Participant 003

R: The first one I'd like to talk about is physical demand. The first stage, so matching the position of the green and red bars with the hand you responded with 70 out of 100. For the second stage, where you were grasping the can with a set force and then wearing the blindfold you responded with 45 out of 100. Then for the final stage, where you wore the hand and used it to pick and place objects, you responded with 55 out of 100. What do you remember about physical demand of using the hand in each of these stages?

003: I remember using muscles in my arm that I wasn't used to using. So towards the end of the exercises it felt a little bit uncomfortable, but not so much that it was painful. I think the blindfold exercise made me feel more in tune with [the prosthesis]. It helped me compartmentalise the feeling and sensation in my arm more than the other [stages]. I think that might have made it more difficult, in a way. I'm not quite sure because I ranked it 45 at the 100, but I remember feeling more conscious of the [sensory feedback]. I think toward the end of the exercises. I became more aware that my arm was aching. Whether that was the use of the muscles that I wasn't used to using or the weight, I'm not sure. I can't quite recall at which one was more a factor. Everything else, from memory, was okay. The strap was comfortable... I think maybe having to twist the arm to pick up objects might have been a factor.

R: Okay. I'm going to ask you about performance now. For that position matching task you said 75 out of 100. For the blindfold task and the can squeezing task that went down slightly to 65 out of 100. Then for the final stage where you were picking up the objects that went up to 80 out of 100. Do you remember what contributed to feeling like you've done well or not on a certain task?

003: I remember feeling a big sense of satisfaction from picking up objects and putting them in a specific place. I think that made me feel like I had more control over my environment, in a way that I hadn't experienced for a long time – since I originally had a prosthesis. The second one I was blindfolded, wasn't I? I think not having that visual stimulus was a factor for me in like having that sense of satisfaction and not being able to, like physically see what I was doing. Although having said that, when I could hear what kind of object it was, that did give me a sense of satisfaction knowing that I'd [identified] it. In terms of what I think I did badly, fumbling with the objects. Not being able to like open [the prosthesis] all the way or close it all the way. Fumbling, like dropping objects. For example, the paper clip. The smaller the object got, the more frustrated I'd get. By the end of the exercises the more practise I had, the easier it got, and I felt like I was doing better. I was getting more used to the types of movements I needed to make. My own coordination as well, I think was getting a bit better. Feeling like I was doing things a bit quicker and more accurately, definitely made me feel like I was successful.

R: Just then you were talking about you felt like you had a sense of control in that you could influence your environment in a way you hadn't felt for... Well, I think you said since you've previously had a prosthetic hand. What prosthetic hand did you have before that and what was it about that that made you feel that way?

003: It was the [split] hook with the elastic bands and can't quite remember the name of it. But you know the one that I mean, you would kind of push it forward and the split hook would open. It was like strap over my shoulder. I remember using that prosthesis to specifically pick up objects and move them and do things like open doors with handles. I think having an additional functionality that I haven't had for quite a few years was made me feel like I could... it was a very specific. Trying to figure out what I'm trying to say... The specific tasks that I was given weren't things that I ever thought that, or the functionality [needed to completed them] wasn't something I thought I needed. I've never thought of myself, as someone who needs the extra functionality that I haven't had for a while. I can get by quite easily just using one hand. But having the experience of picking up objects with my left hand with that [prosthesis] was interesting because it made me feel like there was more it could be like doing or controlling. That's not to say I preferred that. I think I would always prefer to keep going the way that I've been going in terms of using the right hand.

R: That makes sense. Thank you. The next one I'm going to ask you about is frustration specifically. For the first stage, where you are matching the green and red bars with the position of the hand, you had that as 45 out of 100. For the second stage, with the blindfold where you know to identify objects, we put in the hand that was brought down at 10 out of 100. Then for the final stage where you were doing tasks with the hands while you're wearing it, it was 25 out of 100. I think we've touched on it a bit already, but was there anything in particular that made you feel more or less frustrated?

003: It took a while to get the green and red lights to line up, and I think it was like the amount of time it took there was making me more frustrated. Not with you, [R], with my function. It was very easy to kind of flip between one or the other [action], that fluidity made me feel a bit [frustrated]. I think I would have had more satisfaction if it was just like yes or no... maybe that says something about my outlook on life, I don't know. And then yeah, like I said before, I had a lot of satisfaction from picking up objects, like knowing that I'd like got it. That made me feel less frustrated and I felt like I was achieving something; that contributed to me feeling less frustrated. At the same time, dropping things like maybe feel more frustrated. There were specific objects that I had to pick up that were a lot harder. So for example, the paper clip where it was very difficult to get the fingers to close at the right angle or in the exact place I wanted them to. And I was getting frustrated with the fact that I couldn't quite align the arm

correctly with the object, so not that they weren't functioning. It was my control over the hand itself that I was frustrated with.

R: Okay. I'm going to move on to the embodiment statements. The first statement I'd like to ask you about is "the prosthesis in my hand". For all stages you said you strongly disagree – and that's okay. I'm really interested to know what about it didn't make it feel like it was your hand. And what would make something feel like your hand?

003: I'll start with why it didn't feel like my hand. I think it was the look of it; it looked very robotic. It looks like you know how I would imagine a robotic hand to look like. So the appearance is a big factor. Then on the flipside of that, I think that having a more lifelike looking hand would definitely make me feel more like it was aligned to myself. The range of function was less functionality than a real hand would have, so I think that is a factor. In making it feel like whether it's like mine or not because you can look at the other hand and think "well, this can do all this and this, this can't do that". I think it was also the amount of time I'd had using [the prosthesis] – I was with you for less than a day and it was just too short of a period for me to feel like it was part of me. I think with a longer time using it, spending time with it, taking it to bed with you, picking up objects, all of that, I think would personally make me feel more like it was part of me, or is my hand. I think it's probably linked with some of the exercises as well. The exercises were they felt like not 'real' experiences in that we were in like an environment that was in a research lab. They're not tasks that I'd be doing in my day-to-day life. I'm not going to be squeezing an object, picking up random objects. What would make me feel like it was my hand would be to use it in real life scenarios. For example, opening a door or going to the post office and opening an envelope, or wrapping a present or something. In an environment that made it feel like it was my environment, so maybe doing it in my home. Allowing me to choose the objects that I would have been picking up to be something that I was more familiar with or I use every day, I think that would have contributed to feeling like it was more a part of me. Physically, I think the weight was maybe a factor. It wasn't because it was particularly heavy. I think it was just that I'm used to doing tasks without an extra weight on [my arm]. So I think having that extra weight on it made it feel almost more artificial in a way, like there's something there that I'm not familiar with or used to or shouldn't be there. What would help is having something as lightweight as possible.

R: Thank you very much. This next statement is a slightly different angle at a similar topic. This one is "the prosthesis is part of my body". Again, for all of these, you said strongly disagree. What would make it feel more or less like part of your body?

003: That's a good question. I think easy [donning] would help, so not so many straps or things to keep it in place. The additional stuff makes it feel a bit more artificial. Keeping it as simple

as possible would probably help with that. The look of it, again, didn't look like the rest of my body. Making it look a bit more similar in skin tone or shape. The shape of the fingers for example, or the palm was a bit like jagged. The [fingers] weren't curved very well, from memory, and it didn't look very lifelike and. I could talk about my body and the fact that you could feel an extra thing there I'm not used to. I think reducing the amount of skin contacts might make it feel like it was more a part of part of my body... I don't know. I think the feedback that I was getting from certain objects was good, but it was up here on my upper arm. I think maybe having feedback at the lower end [of my arm]. I think maybe having the feedback mechanism like at the bottom like where as close as possible to where the action is happening would make it feel more a part of the body. I found it quite jarring having this feeling in my upper arm, when the actual action was happening down at the lower arm. I think making that change would probably make it feel more like it was a part of my body.

R: That makes sense, thank you for that. This next statement is "my body feels complete". Before we started, you said you agree. After stage one that stayed agree. After stage two that went down to somewhat agree. Then after stage three, so after you'd worn the prosthetic hand, it went down to disagree. Do you remember anything about this feeling of completeness and the effect that the prosthetic hand had on that?

003: I think maybe the more hiccups I had, or the more frustrated I'd get with like certain tasks, maybe I felt a mental detachment or aversion to it. I don't know. I think maybe having more familiarity and time with it would be a good thing in making me feel like "ohh there's more function I can be achieving. There are more things that I could do that I haven't maybe been able to do with an exact functionality that this offers". I think that could probably help with the complete feeling more complete. I think my perception of completeness is based on how other people perceive me as well, which probably isn't a good thing. So I think having a device or an extra and that doesn't look or appear lifelike. Makes me feel like it contributes to me feeling incomplete, in a way.

R: Okay. What is it about it looking specifically lifelike that would make you feel more complete?

003: I think it looking lifelike when it's functioning as well as not actually in use. So it might match me symmetrically, for example. And being able to walk down the street and people not think of it or see it as something that is not completely 100% real. I think that's a factor.

R: The next one we're going to ask about is "the prosthesis is in the location where I would expect my hand to be". When it was on the desk, you always strongly disagreed until you until you wore it, where you said you somewhat disagreed. Do you remember anything about the location of where the hand was relative to your arm that made it feel correct or not for where you would expect to hand to be?

003: I have a feeling that it was slightly longer than my actual forearm. I think if I put my elbows together and put my arms up next to each other it didn't match. It feeling like it was aligned with the other hand would help. So the size and location. Because the socket that held it in place [extended further] up my arm, it made me feel like it goes all the way up here rather than just what was functioning down here at the bottom of the arm. I think that contributed to me feeling like it wasn't quite in the right place. Not that there is necessarily a solution to that, but yeah, having less straps, less bit that kind of crept up.

R: Okay. The next one is "the posture of the prosthesis corresponds to that of a real hand". Before we started, you said you disagree. And then after you used it so for the rest of the study, you said somewhat disagree. So it went up very slightly. Do you remember much about how it moved or how the fingers looked or how they held themselves?

003: Yeah, it was the range of movement was sadly limited. So it could [close] and twist and pinch with the two fingers and the thumb. I think if it had more functionality then it might have helped. Having said that though, I think that having lots and lots of functionality in a short time to kind of learn it in would have probably been a bit overwhelming, and I would have needed more time to get to grips with it and understood its full range of motion. I think the way that it rotated from memory was like quite lifelike actually. Because very rarely would you rotate your wrist inwards rather than outwards, and I remember really liking that. I thought that was good and lifelike. The shape of the fingers, I think they're quite long and spindly fingers. My fingers aren't long and spindly, so that made it feel like when I was picking up objects, it was a bit more tricky.

R: Okay, thank you. The statement I'd like to ask about next is "I am in control of the prosthesis". At stage one, you said you somewhat disagree. After stage two, that went to somewhat agree, and then that stayed there for stage three. Do you remember this feeling of being in control of the prosthesis and what contributed to that?

003: Yes, being able to perform tasks, and practising and being able to make it move in the way that I wanted it to move, the way I was intending. I think I probably made more mistakes beginning and I found it like difficult to rotate, open, close [together]. I think particularly the closing motion – trying to get it to close a certain amount – was quite difficult. It was quite tricky because it was using certain muscles. The feeling that I couldn't quite control that contributed to me feeling frustrated. I think again, with that it's a practise thing, we had a limited amount of time together. I think that was contributing factor. I think maybe if I had more functionality and I had more practise and did more things with it. Again, maybe a more natural environment or an environment that was more familiar with that would make me feel like I had more control over it as well, because I would be able to do additional things and I'd feel more comfortable in

the environment that I was in doing those things. For example, making a cup of tea at home with it, and doing it all with the prosthesis. I think that would have contributed to me feeling more in control.

R: Thanks. The next statement I'm going to ask you about is "the movement of the prosthesis feels like an actual movement". For stages one and two, so when it was on the desk, you said you strongly disagree. Then after stage three, so when you wore it, that went up very slightly to just disagree. Again, I'd like to ask you what factors go into making it feel like an actual movement that you're making?

003: So the feedback helped, but conversely because that feedback was further up the arm, it was a bit jarring. I think feedback was the main thing, having it further down would be a good thing. I think being able to see [the prosthesis] probably helps me feel more confident in my ability to control it. I remember lifting the wrist action with my left arm [to perform a tripod grip]. My upwards was quite uncomfortable. It didn't feel like a natural movement. I don't know from memory whether I was matching it with my right hand at the same time to mimic it, but maybe that would help.

R: Thank you. We've covered all of the statements that I wanted to ask you about. Before we finish, is there anything that you would like to talk about that we haven't talked about so far?

003: No, I don't. I don't think so. I think we covered quite a lot and there's not anything that I think I need to elaborate on. I think maybe the most important factor for me was definitely the environment that I was in.

Participant 004

R: The first one I want to talk to you about is perceived performance. So this is how well you thought you did at the tasks. For for stage 1, when you were matching target positions, moving the hand to a goal position, you said felt like you performed at a 20 out of 100. Then stage 2, after the target forces and then had a blindfold on and identified objects in the hand. You said 25 out of 100. Then stage 3, where you've worn the had done some pick-and-place tasks you said 20 out of 100 again. What it was about each of these tasks that made you feel like you've performed the way you did?

004: Well, I think perceived performance on all three really was just my frustration at not being able to achieve what I should have been achieving. So it was not nothing to do with the test or the hand itself, it was more my frustration. I think that's because, being a split hook user, I'm used to achieving everything each day. So in my mind I'm at a I'm a 90 out of 100. It was frustration. I couldn't... I wasn't able to operate the hand away that I should have been able to. I think the disparity was between my actual prosthetic and how well I use that in my mind, and not being able to use [the research prosthesis] as well.

R: Okay that's pretty interesting. In that case, I'm going to ask a little bit about your perceived frustration to see how it relates to performance. For stage 1, you said your frustration was 50 out of 100. Stage 2 when we were matching the forces and used the blindfold you said it was 100 out of 100. And then after stage 3, where it was picking and placing the small objects or the boxes and blocks, you said 100 out of 100 as well. What's interesting there is that when you just said that frustration was related to your [perceived] performance. Actually, the time when you rated your performance as the worst, which was stage 1, that was when your frustration was also the lowest.

004: [It was a] simpler task probably, in comparison to the other two. It was much easier - it should have been much easier. Then the blindfold thing I just didn't know what on Earth was going on in that... Apart from the can. I remember picking up the can.

R: I'm really interested in your perceived performance on stage 1. Because that was when your frustration was pretty low. So you said that you felt like you only performed at 20 out of 100. What do you think was might have been going on, apart from maybe frustration?

004: Probably getting used to the hand, that muscle movement. Which I felt was quite forced through the three tasks. In my mind, it was a simple task, the first one. Because looking at the screen I can see what's going on. But then when I was unable to achieve that... maybe my competitive edge, perhaps. I just wasn't doing it and it's like, "come on, you can do it". I just felt like I let myself down a bit on that one. All the research that I've done [previously] and all the playing

about with this sort of thing, I should have better at that than I was.

R: I'm going to ask you a bit more about the frustration. You said it was frustrating and we touched a little bit about on why stage 1 was frustrating because you've taken part in research before, you've had experience of how you should be able to control these hands or a perception of that. Then you've got all this reference of how well you can do it with a split hook. But stage 2 and stage 3, you've rated as 100 out of 100. The scale doesn't go higher, so I'm really keen to find out what it was about stages 2 and 3. That made them frustrating. Let's start with stage 2.

004: I think I found stage 2 annoying because I had no haptic feedback. It's very difficult to [know what's in the hand when] you're just moving your muscles. Because those muscles aren't trained, I've had no longevity and training to carry out the task. I didn't get any feedback whatsoever, did not know what on Earth was happening, and in my mind I'm thinking "right, I've gotta do this, that, and the other", but it just wasn't working. That little [sound] for the tuna can, then I could recognise it and the bleach bottle, but otherwise I was literally flapping about the wind. I didn't know what was going on because there was no haptic feedback or any kind of feedback from the hand.

R: So I just, I just wanna ask what exactly you could feel.

004: Honestly, I don't think I could feel anything. It was just my focus on moving my arm correctly. I was carrying out the movement in the muscle. I was solely focused on that and I think once you start with that and it gets frustrating, then you're moving your muscles even more. You're putting more effort into this, the pronate or the supinate or the clench. After a while, you all you can focus on is those muscles and you almost lose sight of the hand and what the hand should be doing. I could not see beyond the end of my arm and those muscles moving.

R: Okay, and for stage 3, what did you find frustrating about that?

004: I've done it before and I did the [Jebsen-Taylor Hand Function Test] with the split hook. I kept reverting back to how I did it with my split hook. I know the functionality is different, but I still have that kind of that [completion] time in my head that I need to get it done by. It was that competitive edge, I think, and also knowing that there's a benchmark and I was trying to beat that with the with the hand. Again, the frustration of [when] the muscles were not moving correctly. Even with the best will in the world, I just don't think I'm [able to move my muscles correctly]. I'm almost conscious not to move the muscles in my arm when I'm in my split hook. Because I know I shouldn't be moving them around in the socket, because the socket isn't designed for that. My arm should just slide in and stay static, really. I think it's just not having the muscles trained well enough to carry out the task. You know, if I was doing this task over the course of two weeks everyday, then I'd have a much better understanding. Also

probably the psychology behind it is that I know that no bionic hand is going to give me the functionality in my split hook. At the moment there's nothing out there that can give me what I've already got and improve upon it. So I go in with a – it sounds terrible, but it's no reflection on the hand – I go in with a cynical view. That it isn't going to behave. It's like dealing with a naughty school child. It just won't do what you want it to do, so frustration is through the roof.

R: I see, that make sense. I'm going to ask you some questions about the embodiment statements that you answered between strongly disagree and strongly agree. The first one I wanted to ask you about is “the prosthesis is my hand². Before we started, you said neutral, then after stage 1 you said disagree, and stage 2, you said disagree, but after stage 3, when you wore it, you said you agree that this is your hand.

004: I think the stage 3, the task was more... I could see what I was doing for a start, and it was more [like] real life. In terms of picking moving things around, that was more of a real-life scenario. That made me think that answer, “yes, this could be my hand”, in a future setting.

R: Okay. So what is it about being able to relate to real life that makes it feel like it's your hand?

004: I think you can imagine yourself in a kitchen trying to pick something up with it. In the future, if it becomes really cool and really affordable, and I end up using one I can see how then some of those tasks could be replicated in my real world. Whereas the previous two tasks you have been blindfolded. I've got sight, hopefully that never changes, and looking at a computer screen isn't the real world. So I think yes, stage three was more... I could see a place for what I was carrying out in my in my life. That made me think “actually this could be my hand”. Or a bionic hand – not my old hand.

R: Okay. I'd like to ask you about this statement that said “the prosthesis is part of my body”. Before we started, so before it was when it was just on the desk, you said you somewhat disagree. Then after we did the position matching, it went down to disagree. After we did the blindfold and the force matching, you said strongly disagree. Then, when you wore it, it went to just disagree again. Could you talk me through any aspects that make it feel like part of your body or not? Or what it was about those tasks?

004: I think it's because it's uncomfortable – the socket isn't comfortable. I think that had a bearing on it, because it just didn't feel [comfortable]. It's as good as we can get it, but it didn't feel like the prosthesis was made for me. I mean, my prosthesis is designed solely around my residual limb; it's custom to me. That probably has a bearing on the psychology that it is mine. That that is my prosthesis or that is my arm, so to speak. A lot of that was the, the uncomfortable nature of the hand. Visibly, it doesn't look anything like something that I would choose. There might be people out there that would choose a red hand. You know what I mean? But that

isn't something that I would go for. If it was black and covered in carbon [fibre], honestly, I'd have more of a relationship with it, because I'm used to black and carbon [fibre].

R: Okay, I'm going to ask you about stage one and two. You weren't wearing the hand [during those stages]. It was on the desk. How about then? How much did comfort have to bear on it?

004: It doesn't look inviting to put your limb into.

R: Could you elaborate on that?

004: I think because we were using it [in previous research] we know how long it was. We knew that it was like crazy length. I think, because of the length of it, I know that the myoelectric control and the functionality isn't going to be there. I'm used to having just the end of my arm and then an attachment at the end of it. I look at that the length of my arm [and the myoelectric hand] – it's not crazy long in comparison, but it's just these are minor details. It's just that little bit longer and I know that the longer the prosthesis, the harder it is to operate. I think that's the psychology of having [my current] arm and using it all the time. Then looking at [the myoelectric hand] and thinking, "that isn't going to be the same". I think it does hark back to how I feel about my current prosthesis. That has such a big bearing on how I feel about yours.

R: Interesting, so even before you had worn it in this study you had it in mind that that was how it was going to go?

004: I'm not able to forget about my prosthesis. Probably because I spend my life working in prosthetics. They're centric to my life. It shouldn't be, but it's kind of ended up that way. Because I'm so cynical about prosthetics, or most prosthetics, that has a bearing. I can't shed down cynicism.

R: Okay. The next statement is "I feel as if I am looking directly at my own hand rather than at a prosthesis". This one's quite interesting – stage 0, before we started, you said you disagree. Stage 1 disagree, stage 2 disagree, and then stage 3 that went up very slightly to somewhat disagree. What was it about stage 3 that made it feel more like you were looking at your own hand rather than that of prosthesis?

004: Probably because of the tasks, because of what you're doing. You imagine your hand doing that... when you had a hand. I think it's all that that was down to the tasks that were being carried out. That made me start to think when a task went well, which was hardly any of them. But there were points when it worked and points when it didn't. But when it worked I was like "ohh actually yeah, that that could be my hand". But that's only a split second because then you do another task and it's not working. Then you want to throw it across the room.

R: Okay. Something about it being useful?

004: It makes me feel like I'm looking at my hand, but not at my prosthesis, because there's fingers

and a thumb. I think that had a bearing on it slightly. If it didn't have the four fingers and the thumb, then it wouldn't look like a hand. Because it was all the fingers and thumb moving, at points, to work together. It made me think of my hand... but only when it works. Imagine if you had an arthritic hand then you had it amputated. You would remember how frustrating that arthritic hand was and you couldn't pick things up. So it's almost all the other way around. You've been more frustrated, because it takes you back to when your hand didn't work. My hands always worked before, I didn't have any problem with them. So when your hand worked, it did take me back to having hands. Which is not something that I ever think about. Maybe when I am frustrated at home. Twisting a bottle top, you know things like that. It's just that split second when everything cohesively work together. But that was few and far between.

R: Right, okay. The next one is "my body feels complete". Before we started, you said you agree that your body is complete in its current state. Then after you used the prosthetic hand, it went down to strongly disagree. That was stage 1 and 2; both were strongly disagree. Then stage 3 it went back up slightly to just disagree instead of strongly disagree. I'm interested to know what it is about a prosthetic hand that would or wouldn't make your body feel complete.

004: I've had two bodies. I had one with arms and legs and now I've got a body with no legs, bit of an arm missing, a lot of the other arm missing. I don't know. I'm not even sure what complete even means for me. I don't feel complete when I put my left arm on, for instance, with my right arm. "Body complete" to me is just wearing that one prosthesis on my right arm. I think through the tasks on the third stage, it made you feel like it was nearly... we're on the way to feeling complete. I honestly... I don't even know what complete looks like for me. I guess I feel complete. Yeah, as complete as I can get. It is just putting my right arm on in the morning and getting in a wheelchair. Two devices and I'm complete. When you're missing so much. If I had legs and a left arm and you were giving me that prosthesis, then I would feel complete, cause everything would mirror. So yeah, I'm not too sure what complete even means.

R: It's okay not to know exactly what complete means. Complete means something different to everybody. I would like to touch on something you said, which was when you put your left arm on - So that's an above elbow cosmetic prosthesis?

004: No, body-powered functional.

R: Okay. So when you have two body powered hands on, you say you don't feel complete when you wear that?

004: No, because I don't wear it enough, so it's not the norm. I put it on intermittently to wear a shirt and maybe if I'm going somewhere where I'm going to do lots of self-propelling [in a wheelchair] and I need both arms to make it work. Otherwise, I wouldn't wear it, or I take it to

universities for research purposes. It feels like a an add on almost.

R: Okay.

004: Whereas the right arm, I wear it 16 hours a day. That's probably as nearest to complete as I can feel when I'm in the wheelchair.

R: Stop me if this is too asking too much. How about when you're not in the wheelchair and you're not wearing your right arm?

004: Yeah, I feel vulnerable. Say I'm on the floor mucking about with the dog. I feel naked, really, without that arm and not in the wheelchair. I guess the nearest I can get to complete is my right arm on and me sat the wheelchair.

R: Thank you for that. I'm going to ask you about statement seven, "the prosthesis is in the location where you expect your hand to be". Of course, before you wore it, you said strongly disagree. When you'd worn it, you said strongly disagree as well. Could you shed some light on that? About what makes it feel like it's where you'd expect your hand to versus where the prosthetic hand actually is?

004: It just, it just feels too long to me because I'm dealing with a residual limb that's only about 6 inches long, with an attachment right at the end of it. There's a big disparity between the length of that arm and hand, and my arm and attachment. It looks long, feels long. So yeah, because it's almost like the same length again away from the my residual limb, it doesn't feel like I've got great control of it.

R: Okay. The next one is "the posture of the prosthesis corresponds to that of a real hand". So that's to do with how the fingers are sitting, how they shaped, how they kind of how they move a little bit. Before we started, you said you agree. Then we did the first task and you said you agree. Then you did the blindfolded task, and it went right down to neutral. After stage three it stayed at neutral.

004: I think to basically to look at before you do any task with it, it looks as near to a hand as a bionic hand could look maybe. Maybe the fingers are a bit too straight. You are still looking at a palm, a thumb, four fingers; to me that's a bionic hand. Actually, have you seen how much more life like the new Bebionic is? It did look really cool. Hate saying it, but it did look really cool. I know it's functionally ****, but it looked great. I think your hand would look better if it had some softer bits if you know what I mean. More curvature. I still think [your hand] looked like a hand because of the four fingers and the thumb.

R: After stage 2, after the blindfold, your perception of that changed?

004: Yeah, because I couldn't see what was going on and I couldn't make out what was happening. It could have been a split hook for all I knew. There was a big disconnect from feeling that I had

thumbs and fingers or something and think and fingers at my disposal. Without any feedback, I couldn't determine whether forefinger was in comparison to where the little finger was. I just could not connect with it.

R: Without that visual reference it doesn't feel like the posture really means anything anymore?

004: No, it could have been like those grippers that you get in the penny slot machines in seaside towns, where you grab the teddy. It could have been that for like, for all I knew at that point with the blindfold.

R: Okay and then stage 3, when you could see the hand again, you were wearing it and doing tasks, it remained neutral.

004: Yeah, the fingers just didn't want to do what I wanted them to do. So I still don't see fingers and a thumb. They just wouldn't play ball. It was still a hand, but the fingers and thumb just weren't working. I wasn't operating the hand well enough to carry out the tasks. The four fingers, the thumb; you can see it was hand. But just couldn't quite do what you wanted to do, or you couldn't get it to move the way you wanted it to.

R: These next three [statements] are all about sensations – what you could feel in the hand. The first one is you “felt a touch sensation in the prosthesis”. You said strongly disagree across the board. How did you feel about a touch sensation with the prosthesis?

004: The only way [I could feel a sense of touch] was because I was looking at it. It was visual otherwise.

R: Do you remember feeling anything from the arm band at all?

004: I couldn't make any kind of sense that armband, to be honest. The trouble with feedback is it's somewhere really random. You know, stick it on the top of your arm or, you know, in the back or when your rib cage. That that isn't how hands work. [The armband] was on skin graft, wasn't it? So I didn't [feel anything].

R: I remember you saying that you could feel when the armband squeezed a bit.

004: Yeah.

R: But you couldn't make out individual fingers.

004: No.

R: OK, so in that case, I'm gonna ask you about the next one, I can “feel the position of the prosthesis”. So stage 1, you said neutral, after you've been controlling it to a position. Stage 2 that went down to disagree. And then stage 3 it went back up to neutral. Do you remember what it was that let you feel or made it feel like you could or couldn't sense the position of the prosthesis.

004: Visual [feedback] and weight. You could feel when it was to the side, you could feel when it was flat. I think that's just the weight of the arm itself, and the way it was moving the residual limb. The visualisation in the third test, where the hand was positioned.

R: Okay. The next one is you could "feel the force being applied by the prosthesis". For this one, after stage 1, after the position matching, that went up to disagree. After stage 2 that went up to somewhat agree. After stage 3 it went down to disagree again.

R: What do you remember feeling the force of the prosthesis? It's that sort of squeezing around your arm.

004: If I gripped tight, it was that, just that pressure on the muscle.

R: Okay. The next statement is "the prosthesis moves the way you want it to move". After stage 1 you said neutral, so after that was after position matching. Then after force matching and wearing the blindfold [in stage 2]. You also said neutral. Then after stage 3, it went down to somewhat disagree. What do you think had a bearing on that feeling of it moving the way you wanted to move?

004: It didn't do what I wanted to do all the time. So I couldn't understand what was happening.

R: Could you elaborate a little bit about maybe an example or two of when you wanted it to do something and it didn't do it?

004: [I wanted to] carry out every task that was put in front of me with it in a good time, as well as I use my other prosthesis. That would have been like the ideal benchmark. A lot of the time my muscles were tiring. It would take a long time to carry out what I was doing. There was a lag. Other times where I thought it was going one way and it was doing something else.

R: So a lag and when it would start doing something you didn't want it to do.

004: Not having the muscles trained well enough would have been my fault, not the hands. I remember having trouble with those tasks. I can't remember whether one went a lot better than the others. I remember stacking those connect four pieces. That was frustrating. Maybe it wasn't the movement at the fingers... maybe it's just that there wasn't enough grip on the finger itself for some of those tasks.

R: I see. The next statement is "I am in control of the prosthesis". So after stage 1, you said you agree. After stage 2, you also said you agree, and after stage 3 that went down to neutral. What is it that makes you feel like you're in control of the prosthesis? And what was it in stage three that made it feel like you weren't as in control the prosthesis?

004: The first [stage], I suppose because it was, it was reacting to my muscles moving, so I felt I was in control of it. The third test was because I was not carrying out the tasks well enough. I

probably felt that it wasn't doing what it should have been doing, and I felt my muscles were doing what I was asking them to do.

R: That makes sense. Okay, the last statement is "the movement of the prosthesis feels like an actual movement". After stage 1, you said you disagree. After stage 2, you said you agree. Then after stage 3, you said neutral.

004: I don't know why I said I agree in stage 2, in hindsight. I suppose I couldn't see it; I just thought everything was working correctly. Maybe what's happened.

R: Yeah. And then stage 3?

004: Again, just that frustration.

R: What's interesting is the difference between stage one and stage three is it's actually up. So stage 1, you said you disagree, and stage 3 it's up to neutral.

004: Stage one it's on a computer screen – there's no link to real life. Stage 3 it'd go up because there was a link to real life.

R: Okay, I've finished all my questions. But now I'd like to give you the opportunity, if there's anything that you'd like to talk about that we haven't talked about, now would be a great time.

004: My frustration is there's an assumption that myoelectric and is going to be better than split hook functionality. Really, I don't see the cost benefit. Sure, you get the aesthetic [with a myoelectric hand] that people want – fingers and thumbs – but you know, to me as a double arm amputee. I have to err on the side of function beyond aesthetics. A multi articulated limb is just not good enough for what I need to do. I think it's nuts that there are people that are driving the policy, who don't have any concept of the functionality of this equipment. It's just frustrating. That they feel that, because it's myoelectric, it's state of the art. That "it's obviously going to be a better prosthesis", but that isn't the case. I don't know any prosthetists out there that would say that the iLimb or the Bebionic has more functionality than a split hook. And if they did say it, they would be lying. From a research standpoint, I don't see why we're not looking into more hybrid prostheses, whether it be myoelectric or whatever with body powered. It's like we've jumped from a Ford Model T4 to a Tesla, and not tried anything in between. I did quote recently, it was to a journalist, I did say that supplying Ukrainian soldiers with myoelectric multi articulated limbs is like getting in a Tesla to drive through the mud on the frontline. ***** useless. To which my prosthetist and my plastic surgeon wholeheartedly agree. So these guys are agreeing with me in relation to the functionality that split hook, so why more people aren't looking at that? Who is making those decisions? It's not end user led... it should be end user led. I'd like to see more. The amputees are willing to give their time into these research projects and studies. They should have more voice into what goes into the system than anyone

else, cause they're giving their time to develop, to understand, and teach. You know, I think we should have more of a voice.

R: Thank you.

Participant 005

R: The first thing I'd like to ask you about is mental demand. After the first stage, matching the bars with the position of the hand, you had that down as 60 out of 100, so about 60%. After stage two, so after squeezing the can and then putting on a blindfold and identifying objects, you had that up at 95 out of 100; nearly as high as it could go. Then when you wore the hand and did tasks in stage three, you have that down as 45 out of 100. Do you remember what contributed to feeling like there was more or less mental demand while using the hand?

005: Yeah. Because I'd done it all day, by the last stage it felt like I was getting into the swing of it. It was like learning a new skill to start with, because I've not had a lot of experience with any prosthetic hands, certainly not robotic ones. So yeah, it was like learning a new skill. Once I had it, I felt more physically tired than I did mentally because I'd got used to using it and I felt a bit normal.

R: That makes sense. What about at stage two?

005: That was because it took away your other senses. So obviously you keep touch and smell and taste and all the other senses, but sight is a big one. Trying to figure out what [object] it was, and my competitiveness wants to get every object right, but it's just not just not plausible, really, is it? Because some of them are quite similar, I found that really mentally taxing. At some objects I didn't want to guess, but I couldn't tell. There were certain objects I could tell what they were. If I had to squeeze tighter to grab it, the armband went tight around your arm and the sensation was around all the fingers rather than just one or two. It was hard to link that to what the hand was doing.

R: Thank you. The next one I'm going to ask you about is physical demand. For every single stage here, you put this as 100 out of 100.

005: Yeah, I found it really, really strenuous for my arm because I'm just not used to using it. I won't say [that my arm] sits by the side of me, but it doesn't get a lot of use. I'm very much dominant with one hand and I was doing everything with the other. The muscles, although they felt pretty powerful when we did the test, repeatedly using them was difficult. The endurance of it was hard.

R: You've given the same response for every stage, but how did you find wearing the prosthetic hand?

005: It was quite hard. It was quite a heavy piece of equipment, so securing it on your arm and functioning with it was difficult. I mean, if there's a chance of making it lightweight, I'd recommend it. The higher up muscles as well, in my shoulder, were tired from holding it up. I felt like I had to... it wasn't a natural elbow lift, it was more about getting underneath it and propping it up sort of thing.

R: Alright, I'm going to ask you about frustration now. At the first stage, the position matching stage, you said 85 out of 100 for the amount of frustration. For stage two, the blindfolded one and squeezing the can, you said 100 out of 100. Then for stage three, where you wore it, you said 55 out of 100.

005: Stage one, it's going back to learning the new skill. I didn't find it easy. Whenever I've done sports I've always picked up a sport pretty quickly, and I just didn't find I was picking that skill up very quickly. So I found it quite frustrating to start with, and then it didn't help that in stage two I couldn't identify some objects. I think it was the bottle and the sponge, because the sponge was so soft, it didn't really feel like anything on my arm until I was closed tight. It was similar in size to the bottle, and I'd try to time when the armband went tight on my upper arm. I just couldn't figure it out. I was trying to use every different part of my brain to be better at it, and I wasn't.

R: Okay and then for stage three, when you were doing the tasks, this went down to 55.

005: I think the blocks, I wanted to be the best at it. I very much was putting a lot of pressure [on myself] and then I couldn't grab two at a time. Well, I could, but not every time.

R: So that was what made it somewhat frustrating. Is there anything that made it less frustrating?

005: Yeah. By the end of it, I felt like I was getting into the swing of it, doing better with the bottle caps and the paper clips and the pennies and stuff. The smaller objects, I felt I was better at picking them than I was the blocks.

R: Interesting. We're going to move on to the embodiment statements now. The first one we're going to do it "the prosthesis is my hand". Before we started, you said strongly disagree. After stage one, you also said strongly disagree. After stage two, you also said strongly disagree. Then after stage three that went up to just somewhat disagree. So I was wondering what was it about stage three that made it feel more like it was your hand specifically?

005: I just want to clarify the strongly disagree, because I knew full well that it's not my hand because I'm a human being. I understand that. At stage three, I felt like it was strangely like putting on a pair of trainers. If I went into a shop and bought [the prosthesis] then it would have been my hand. I felt like I could go in and use it straight away, and I'd be comfortable using it. I've never used a robotic arm before, and I've never even really seen one in person, so it was very foreign to me right at the start. But then when I was a lot more comfortable with it – by the end of it – I felt like I could go and use it. If I walked into the room tomorrow, I wouldn't be uncomfortable putting it on or anything like that. I'd probably remember how to strap it up and use it.

R: That's pretty interesting. Was there anything specifically about stage 3 that made it feel like that?

005: Yeah. The more I used it, the better I felt about using it. I was more comfortable with it. I don't understand how to explain it, really, but it felt a bit normal.

R: Stages one and two, the hand was mounted on the desk.

005: In stage three, it wasn't just sat on the desk looking at me or not looking at me. I was moving it as part of my arm.

R: Okay this next one is "the prosthesis belongs to me". Again, at stage zero you said strongly disagree, and it stayed that way after stage one and after stage two. Then at stage three, it went up to somewhat agree.

005: I remember feeling like if I did go into the doctors and got a prosthesis, I'd be really comfortable with it. I remember when I was a younger man, well, when I was a child, I had a prosthetic arm. It was very basic and it just did the opening and closing, and I had a battery pack that came through my clothes and stuff. I had one of those and I was never comfortable wearing it ever. I didn't like it. This one, I thought it could definitely increase my quality of life.

R: Okay, and what is it about this idea that it could increase your quality of life that makes it feel more like it belongs to you?

005: It made me want it. It made me want something like it. Obviously [the study prosthesis] was a prototype, but it made me want it made me look into getting a prosthetic hand. I haven't got one, but it did make me look into getting one.

R: The next the next statement is "the prosthesis is part of my body". Before we started, you said strongly disagree. After stage one, so after position matching, you said strongly disagree. Then after stage two that went up to somewhat disagree. After stage three that went up to agree.

005: I felt I was thinking it, and then [the prosthesis] was doing it. It was more of a natural [process]. By the end it wasn't "right, contract this muscle", it was "pick that up". Then I was doing it as a natural reaction. The thought process was different, rather than the physical act was. I was obviously doing the same thing [physically], but my thoughts going into it weren't "tense the bottom muscle to make sure that you squeeze", it was "right, pick up that penny" or "pick that bottle cap up".

R: Okay. So was there a difference between so stage two where you had the blindfold on to stage three? Was there a difference you felt between those two?

005: It was this extra step in the thought process [in stage two], where it was "squeeze this muscle to close the hand". By the time we'd gone for lunch before we got to stage three, I don't know if you remember, because it wasn't round my round my arm, it felt strange. I remember it felt lighter. It was like there was something missing because it was lighter.

R: Very interesting. The next one is “I feel like I’m looking directly at my own hand rather than as a prosthesis”. So stage zero, before we started, you said strongly disagree. Stage one, that went up to neutral. Stage two, after you had the blindfold on, that went down to somewhat disagree. Then after stage three, when you’ve used it, that went up to somewhat agree.

005: So like I said, obviously it’s not like I’m looking at what would you say normally is your hand, because it’s a bionic arm. But after I’d used it... I can’t explain it. It’s a weird feeling because I’ve never had one. I’ve never had a hand before, so I don’t know what it feels like. When people check the backs of their nails, they put their hands out – I felt like that’s what I was doing when I was holding out the arms together.

R: Okay, that makes sense for stage three. What about stages one and two?

005: Stage one, knowing that I’d tensed the muscles to get [the prosthesis] to move; to close and to twist. I felt like “I’m in control of this, this is me”. Then after you took my eyes away, and I didn’t do very successfully without the sight, it didn’t feel as much that it was me. It was something else.

R: Thank you. This next one is “my body feels complete”. Before we started, so as you are right now, you said strongly agree. Then after stage one and it stayed this way for the rest of the study, you said neutral. What was it about using the prosthetic hand that made you feel more or less complete?

005: I’ve been born with my arm, so I’ve never known anything different, so I 100% feel complete all the time. Then I realised that actually I’m probably missing out on something – and it sounds stupid – but like an easier way of living. There are certain tasks that are difficult for me, they’re not physically really difficult, but they’re more difficult than they should for things such as tying your shoelaces. It takes an extra 20 seconds. Opening a can. Using a knife and fork. I can do it, but it’s more difficult; you have to switch with a fork. You put the fork in, then hold it down with your arm, then cut with your hand. So yeah, I got that first sense of feeling that I was missing out on something to make your life a lot easier.

R: Okay. This next statement is “the prosthesis is in the location where I’d expect my hand to be”. For all of the stages while it was on the desk you said strongly disagree, of course. When you wore it, you said strongly agree.

005: Because it was just a prototype, it was very much bigger than my hand, but I have a little baby hands, really. Once I had it on, it was having the full length of the arm. It was more or less where it should be. Usually I use my arm as a hand for clapping and for lifting stuff and whatever, but having the full length, it put the rest of my body back into line.

R: At the end there, you said “back into line”. Could you elaborate a little bit more on that one?

005: So if I'm picking something up off the floor I have to really reach down, so it's uncomfortable almost. Whereas with this I wouldn't have to do that.

R: Understood.

005: Say when I was picking the coins off the table, I found my depth perception on that side was very different. I felt like I was going past it a little bit, to pick them up. I'm used to having to lean in, having to be close to something. Whereas then I could be touching it from a distance.

R: The next one is "the posture of the prosthesis corresponds to that of a real hand". Before we started, you said you agree. Then you used it in stage one and stage two and you said you strongly agree. Then after stage three it went down again to agree.

005: Yeah, the fingers are really long. You don't notice that when you just clenching and twisting, but when you come to the finer details of picking stuff up like blocks you notice it. They sort of like get in the way. I was trying to emulate what I do with my good hand, but I couldn't always do it; I'd knock another block over whilst trying to grab one because the fingers are a bit further on than I thought they might be. Which is good, in a sense, because if they are long then I'm noticing that, I'm feeling like it's my fingers that are doing it and the same size as my fingers that are doing it. You understand me?

R: Could you explain a little more?

005: Say I've got to pick something up with my left arm and my finger knocks something. It's because I've gone too far. Then if I'm using this prosthetic arm and the fingers are longer than my other fingers, I would go for the same distance and probably knock stuff off. It's a good thing. It's not good that the fingers are long, it's the evidence that I sensed that there were longer when I used them. It made it feel like it was more like my arm.

R: Right. This next one is "the prosthesis moves the way I want it to move". After stage one you said neutral. After stage two that stayed at neutral. Then after stage three that went up to agree.

005: I think it's because of the finer details. Stage two with the blindfold on, it was hard because it was sat on the desk. Then when I put it on, I could feel... it's weird. I can't explain it very well. It's a strange sensation. I felt it in my upper arm that I was grabbing something, but I couldn't see it. So once I could see it as well, once I was doing stage three... Being able to react to the hand. If I tense too hard or not enough, I could then react to it and tense again. When I was grabbing objects, when I could see the object. I think using your other senses to do things. With the blindfold, I could hear the can; I used another sense [apart from the feedback armband] to identify that that was a can as well. In the last stage there was sight as well, so I had more ways of knowing I was doing it well. Because it was a brand new skill.

R: Okay, this next one is “I am in control of the prosthesis”. Now for stage one, stage two, and stage three, you said strongly agree. What was it that made it feel like you were in control of the prosthesis?

005: The fact that you had measured my arm to start with. You’d measured what I could do. Then as soon as I could that I was doing the actions that we tested. And the actions made the hand do stuff. I was like “I’m doing this. This is me doing this”. It was instant; that was me.

R: All right. This last statement is “the movement of the prosthesis feels like an actual movement”. After stage one, you said you somewhat agree, then stages two and three you both said you strongly agree.

005: Yeah, in stage one, I think it was more of a case of it wasn’t doing anything; like it was just closing and twisting, whereas I was actually grabbing things with it [in the other stages]. I was doing tasks with it rather than it just closing and twisting and showing the movement that it has.

R: That makes sense. What is it about it doing tasks that makes it feel like an actual movement?

005: I felt like it was doing the tasks; I was sat there thinking “ohh I’m doing something with an arm” and not I’m not making that hand close and twist. I’m grabbing things. It went from a making that hand close and twist to grabbing things.

R: Great. Okay, that’s all the statements that I wanted to ask you about covered. The only other thing I want to ask you about, is there anything that you’d like to talk about that we haven’t talked about so far?

005: What you’re doing, bear in mind I’m a 31 year old man that’s got 31 years of not having an arm. If stuff like this can be developed for the younger people, I think it will improve our quality of life massively.

R: That’s very kind of you. Thank you very much for taking part of it, because we can’t do it without people like yourself volunteering for research.

Participant 006

R: Before we start the main questions, here's a quick refresher of what happened. There were three sessions in the study. The first session we showed you a series of target positions for the hand to move to, and they were green bars and you had to move those red bars to get close to them. That session was called position matching. In stage two we did very similar, where we grabbed hold of a can and squeezed on it and that was matching the force. Then we put a blindfold on you and got you to identify objects. That was stage two. Then in stage three you wore the prosthetic hand and did tasks with it, like picking and placing the blocks and stuff like picking up paper clips. Cool, so that's a quick refresher on those. The first statement I wanted to bring up is "the prosthesis is my hand".

006: Yeah.

R: Before we started, you said strongly disagree. After stage one that went up to somewhat agree. Then after stage two, so after the blindfold and grasping the can, it went down to just neutral. Then after stage three, it went up to agree. I was wondering if you remember much about it. What were you were thinking at the time about the prosthesis being your hand?

006: I think it was probably more when you had the sight you could visualise and feel the arm more. Obviously in the second part when I was blindfolded, I was only going off what I thought I was doing and sometimes it didn't feel like what I wanted it to do. When I was grabbing the objects and I was getting the feedback from the [haptic armband] on my arm, I couldn't always feel or tell what I was grabbing; sometimes I could, and sometimes I couldn't, so it didn't always feel like I was in control. But when I had my sight, I could visualise and feel what I was trying to do as well, and I think that helped to use the arm.

R: I'm interested to know a bit about that. You said that when you can see it, that made it feel more like it was your hand. What about seeing it makes it feel more like your hand?

006: I don't know, I just I guess it's cause you're using more [of your] senses so it just feels it because you can see something happening. It just feels more real, I guess. I suppose it's like when you're watching movies, sometimes you feel like you're involved, even though you obviously just sat down and you're not there and... I don't know what you're like, but sometimes I react to stuff moving on the screen, and I suppose it's nice. The visual aspect. It just gets you involved a bit more.

R: Okay, the other thing you mentioned there was that you could feel like you control it. I'm interested in this. What about that relates with it feeling like your hand?

006: What do you mean by that?

R: So you mentioned there that when you took the blindfold off and you could see, you had the feeling

that you could control the hand. I was wondering about how that feeling of being able to control it relates with it being your hand specifically.

006: I don't know what to say. Suppose when you try to do something... Obviously with my dominant hand I just move it and I don't think about it, but I suppose when I'm trying to [use] the muscles in my arm to make it do a specific action, and when I can sort of see that while I'm doing it. That probably makes me feel like, "yeah, I'm in control and I'm the one that's doing this" and it kind of feels a part of me then.

R: OK, so like this link between seeing it do what you're telling it to do.

006: Yeah.

R: The next statement I'd like to ask you about is "my body feels complete". At the start, you said strongly agree; you're complete. And then as you [progressed] through the study that actually decreased. So, after stage one it went down to somewhat agree. In stage two went down to somewhat disagreed. Then in stage three, when you wore the prosthetic hand, it went back up again to somewhat agree. I was wondering about your thoughts on that side of things.

006: Can't remember to honest... what was the question?

R: The statement was "my body feels complete".

006: I can't remember. I don't know what that was in regards to. So when we started, what did I say to that?

R: You said strongly agree. So if I asked you now, do you feel complete? Like does your body feel complete?

006: Ohh yeah, I see what you mean... I don't know. I suppose it's again, it's because I've towards the end I could probably see I was controlling the arm. I knew that wasn't a part of me, but I suppose it kind of took away a bit of control from me using my arm to obviously have the prosthesis doing the work for me.

R: I'm not going to press on anything that you don't remember to you all that well, so let's move on. I'm interested in the amount of frustration you felt while using [the prosthesis]. You put that as very low [for all three stages], you it put down as 10 and then 15 and then 10 again.

006: Yeah. That's probably just down to me just being quite calm and collected. It takes a lot to really stress me out. And I suppose it's cause I knew that it's always a learning process as well. It's like when you're starting your job, you don't particularly get too stressed because you know you're still learning and you don't quite know what you're doing yet. If I knew fully how to use [the prosthesis] and I should be in full control, and if stuff won't work out, then I probably would be a bit more stressed and annoyed. But because I know that it's early stages and it's

stuff can go wrong and will go wrong I just shake it off and think “it is what it is” and it’ll get better.

R: Thank you. The next statement was, “I feel as if I’m looking directly at my own hand rather than that of a prosthesis”. At the beginning, you said strongly disagree. But then [after stages 1 and 2], you said somewhat agree. Then after you wore it, you said agree. It was pretty positive throughout [the study]. Do you remember how you felt about this?

006: I think on the table [before the study] it was it just on its stand, it was just like a floating hand. Quite obviously don’t feel like it’s part of you. It doesn’t look particularly like it should be a [functioning] hand or anything, just look like a model as it was on the table. But then when you put it onto the rest of [my] arm and then you start wearing it. Without the skin texture and clearly looking like an arm, it represented an arm, and that’s what you’re aiming for.

R: You mentioned the skin texture and stuff like that, how important is that to you?

006: Me wouldn’t particularly bother me if it was a close match, but not perfect. Other people would probably [say that] “it has to be a perfect match or else it’s just not gonna work for me”. That’s just a reflection on me; I’m quite chilled and relaxed about stuff.

R: Okay, so was there anything in particular about the hand that you thought that makes it look more like a hand or that makes it look less like a hand apart from the colour?

006: Don’t think so. It was kind of what you’d expect in the functions and the movements. Obviously, you could see all of the springs and all of the screws and whatnot, but when the movements are finalised and are in pretty good shape, you’d put probably like a silicon skin over top. Something like that and it’d smooth all out and it wouldn’t be far off then, would it? For the shape and the way it looks, it was about right.

R: The next statement this is “I could feel the force being applied by the prosthesis”. This is that feeling that you were being sort of squeezed or poked a little by [the haptic feedback armband]. That peaked when after we did that blindfold test. Then when you wore the hand, it decreased slightly, so it went from strongly agree just to agree.

006: Yeah.

R: On that one, do you remember how the feeling was when you were doing it?

006: Yes, when I was blindfolded, depending on what objects I grabbed, so I think it was the can. When that squeeze that as much as I could, it was pressing harder, so I could feel like it was supposed to be gripping something. But the smaller the object got, the less of the sensation of force I could feel from the feedback. I think when I could see visually you kind of less focused on that feedback. I could feel it sometimes depending what I was grabbing the cans [in the Jebsen-Taylor Hand Function Test]. I could feel it cause it was quite a strong press, but the

smaller objects she couldn't quite tell all the time. But yeah, I think when I was blindfolded, I could definitely remember feeling presses around my arm when grabbing the bigger stuff, but the smallest stuff I can vaguely remember it pressing, but it was hard to define how hard or what it was at the time.

R: The last three things I want to ask you about. There was a statement which said "the prosthesis moves the way you want it to move". Similarly, "you are in control of the prosthesis". The final one was "the movement of the prosthesis feels like an actual movement". For all of those, for the first two stages you responded with somewhat agree. Then on the final stage they increased to agree. Do you remember if there was anything different when you put on the prosthetic hand and did the last stage?

006: I suppose it's probably [because] I felt complete. It was a part of me then when I was trying to do stuff and it was reacting to how I wanted it to [move]. I probably said that's why.

R: I'd like to ask you about physical demand. After the first stage you rated it pretty high, at about 80 out of 100. The second stage was down to 45 out of 100. Then the third stage is up at 85 [out of 100], so it's right up there. Do you remember the physical demand of each of the stages?

006: So the first stage was when we were trying to calibrate it and trying to fine tune it. So I think that was cause the muscle groups don't particularly get work that often; I think it was just a fatigue factor. The longer we went on the more tired it got and the harder it felt. I had to take a few breaks and I think that happened a bit more as we went on throughout the day. The second bit was when I was blindfolded and I was only grabbing objects, so it was only short bursts or what I was trying to do, so I rested in between, which helped and didn't feel as physically demanding. Then the third stage when I was wearing the arm. It was quite heavy as well; you've got that to play with as well as the fatigue of the muscles. I think don't recall any other factors, I'd say that was about it.

R: Cool, that was the last question [related to the results] that I have for you. I did want to ask you a couple of other questions that aren't related to the results themselves.

006: Yep.

R: I remember, you mentioned that you've used prosthetic hands when you were a lot younger. I was wondering if you had any thoughts about how the prosthetic hand you used in the study compares those that you've used before.

006: The one in the study had the rotation of the wrist, which was different. So that was a new concept for me. Function wise open and closing, it was very similar. I think my old arm it just opened and closed. It got in the way, I found, more than it actually helped. Probably cause of the way it just didn't feel like I could do much because I couldn't rotate the wrist. You very

limited to the to what you could grab and you've got to move around more to get into a position [where] you could grab whatever you're aiming for. Cause obviously [you use] the flexibility of your wrist to obviously get into the position that it needs to start with [to pick something up]. Also, probably cause I was younger [when I used a prosthesis previously], the arm [in this study] felt smaller than the one I had from the hospital. The fingers felt a bit longer, but I think that's probably cause the hand on the [prosthesis] from the hospital was more curved and yours is quite straight, and has quite elongated fingers. That's probably just probably just a design bit, but it's not the be all and end all. I wouldn't say there was all that much difference between them.

R: Do you remember how young were you when you used to the previous one?

006: I had it from being really young to the first year or two of high school. I'm not sure how old you are when you're in year 7/8.

R: Like maybe 11/12/13.

006: Yeah 11/12, so I think it from probably been about... I did maybe 5 till yeah 12 so maybe 6 years.

R: Okay, you may not remember, but how did it open or close? Was it either open or closed or was it able to go like halfway?

006: Um, it could open or close fully and stop at any point in that, like this sort of range, it just depended which electrode I was pressing to obviously open or close it, so I had a bit of control, but sometimes it just kind of did what it wanted. Sometimes it just opened when you're trying to close, and then sometimes it close and you can't open it.

R: And how did the control of the one we used in the study compared to that?

006: It was very similar in the respect of the open and close. But as I said the one in the study had the rotation as well. I don't really know how many arm is built up, it's hard to say, but I've got quite good control in the end of my arm. That probably helps cause then I can kind of choose what I want [the prosthesis] to do a bit more, whereas if I suppose if I didn't have that sort of movement or the ability to control it. It would be hard to try and define an open or close cause you can just feel like you're tensing the whole arm, which would probably give mixed signals, which probably could be what happens with [some] people, I'm guessing.

Participant 007

R: The first one to ask about is frustration. As a quick refresher, stage 1 was matching positions, so moving the hand to a set of positions. Stage 2 was grabbing hold of a can with a certain amount of force and then putting a blindfold on and identifying which object was in your hand. And then stage 3 was wearing the prosthetic hand and doing some pick and place tasks and picking up paper clips and stuff like that. So at stage 1, you said your frustration was about 50 out of 100, so in the middle. After stage 2, you said it was 30 out of 100, a bit lower, and then after stage 3 you said it was 15 out of 100, so quite low. How much do you remember about feelings of frustration? Could you elaborate on any of that?

007: Yeah, so initially I felt like I got to grips with the movements pretty quickly, but then still within that first stage, what I found was that I was struggling to control between a full hand grip and the [tripod grip]. So that was like the primary source of frustration that I was feeling there. But then as we were going on through the day, I did start to kind of get to grips with it a little bit more and especially into some of those later tasks when we weren't using the [tripod grip] I was really happy and not feeling too frustrated. It was that 1 grip that was causing me that level of frustration.

R: So when we were doing tasks that didn't really require that grip [meant that] frustration went down. So when you found it difficult to control it between fully grasping and doing the tripod grip; what about that specifically made it frustrating?

007: I think how close I knew I was to get in that grip. I think maybe the muscle action that we'd gone for [to perform] the tripod was one that was slightly harder for me to do, whereas the full hand grip was just like a big contraction, a big squeeze. I could do that like 10 times out of 10, but the tripod took a lot more concentration for me to do. Especially when the hand was on the on the stand, I could see that it was starting to do it. Then it would turn into a full hand grip and I'd be like, so frustrated by that, knowing that I was really close. Not being able to kind of finish off that movement.

R: Okay that makes sense to me. The next one I want to ask you about is physical demand. After stage 1, position matching, you put it up at 85 out of 100, so that was pretty high. After stage 2 it was 65 out of 100, so a little bit lower. And then after stage 3, it was 70 out of 100. How much do you remember about this feeling of like physical demand and exertion?

007: Stage 1 was tricky, I guess, cause [I was] using muscles that I don't use very frequently and really having to try hard at that. Force matching as well, like some of those were pretty high targets. So that was a bit of a challenge to get up to there and maintain. It was tricky, it's a longer contraction that I was finding a little bit difficult. And then sorry, just remind me, stage 3 was

the pick and place, wasn't it?

R: Yes.

007: So, there's a bit of fatigue in there from actually controlling the weight of the arm as well. Like I found that the box with the cubes in it, that was about as much as I could do without having the sling on. I don't think I've been able to do much more without the sling supporting the weight of the arm.

R: So when there hand was on the desk, a lot of [the physical demand] was coming from your muscles directly, which you don't use often. Then when you were wearing the hand, it was a lot more about the weight of the prosthesis.

007: Yeah. So I wasn't too aware of like fatigue in the muscles that I was using to create the action. It was more fatigue in my bicep and my shoulder that was starting to come into play there from just holding the arm up in that forward position while I was doing the tasks.

R: Okay. The next 1 will ask you about is mental demand. For stage 1 you said that was 80 out of 100, stage 2 that went up to 90 out of 100, and for stage 3 it went down to 35 out of 100.

R: What about the different stages made them more or less mentally demanding?

007: Kind of similar to what I've already said. I think that first stage was like learning it. I really had to concentrate; it was something that was new to me, and I was having to give it my full attention to have success. Then especially while I was having that level of frustration between getting the tripod grip to go, that was really difficult to focus on. But then kind of moving towards stage 3, I actually felt like I was having, like a reasonable success rate like I felt like I was doing okay at the tasks. It felt a little bit more intuitive than matching a position or really focusing on matching a grip level. That, to me, was more mentally demanding than picking up a block and moving it to another side of the box, or picking up a can.

R: That makes sense. I'm going to go into the embodiment questions now. The first 1 I want to ask you about are the statements that said "the prosthesis is my hand" and similarly, the statement that said "the prosthesis belongs to me". For stage 0, before we'd started, they were strongly disagree. After stage 1 and stage 2, for both of those, you put somewhat agree. Then after stage 3, that increased to agree. Do you have any reflections on what it was about using the hands at each of these stages that made it feel like it was your hand, or it belonged to you?

007: Yeah, so stage 1 and 2, I was aware that I was in control of that hand. I was in charge of it. I was using it how I wanted to use it. Then in stage 3, after wearing the hand in a position that I would expect a hand to be, and using it to perform tasks... I had had the arm on for quite a long time by then as well, and it even got to the point where if you had to like retake control over the hand for any reason. I was all of a sudden really aware of the feedback that

I was getting through my through my upper arm, whereas when I had the hand on and I was performing the tasks, that kind of just melted away into the background a little bit and it was what I would expect to feel. But when you were controlling the hand, it felt weird because like it almost felt like you were controlling me, which was really strange.

R: This feeling of you being in control of [the prosthesis]. What is it about that that made it feel more or less like your hand?

007: I mean, that's kind of what owning a body part is like, isn't it? Like you expect it to do something and it will do it. For the movements that I was really comfortable with in that first session, like the grab and the rotate, I felt really comfortable doing those and combining the movements. But then I was still experiencing a little bit of difficulty with the tripod and the hand was sitting on table so I think it was the difficulty with the tripod and where the hand was positioned, that stopped me from feeling like it was fully mine. Having that ability to close the hand and then rotate it. By the end, that was quite easy for me to do, so it that kind of led me to feeling some kind of ownership over the hand. Even more so once it was on and I was having some success with tasks, it did start to feel quite natural.

R: And then I'm going to ask a little bit more about that. So that increase at stage 3, where you say that because you're it was on you and you were wearing it. What about it being on you? Is there anything specific about that, that made it feel more like your hand?

007: It kind of sounds silly, but like proximity to me, like it was exactly where I would expect a hand to be. I have a prosthesis that I use in the gym. And it was a similar length, probably a little bit longer, but not too far from the length that I'm accustomed to with my prosthesis that I use in the gym. There was familiarity there. The feedback almost made more sense because, again, there wasn't that separation between me and the hand - it was on me. Then I was feeling the feedback in my arm as well. It all just kind of like added to the feeling that that was my hand and I was using my hand to grab blocks.

R: Interesting. I'd like to ask you about the next statement, which was "the prosthesis is part of your body". Now for this one, after stage 1 it was neutral, then stage 2 it was somewhat agree. Then after stage 3 it was agree. This is slightly different to it being your hand or belonging to you. So I was wondering if you could elaborate a bit more on what it was that made the prosthesis feel like it was part of your body or not part of your body.

007: Yeah. So I think this one was down to like the time that I'd been in control of the hand. Very early on, it was like I was having some success with movements, but it was still very unfamiliar; [it] was a strange thing to be doing. As I got more used to it, I just got more comfortable with that piece of equipment [such] that it started actually feeling more like part of my body. Again,

that final stage was actually wearing it and using it. [It was] moving my upper arm to help target something, it just all started to feel more like part of my body.

R: Okay. I'm going to ask you about the statement which says "my body feels complete". Before we started, without any prosthetic hand on, you said you agree that your body feels complete. After stage 1 that that reduced to somewhat agree. But then after stage 2 and 3, it went back up to agree. So I was wondering what it was about any of these stages or using the hand that made your body feel more or less complete.

007: Yeah. Coming into [the study], I don't use a prosthetic for day-to-day life. I use it for like sports related activities, no day-to-day tasks. For me, unless I was in a sporting environment, my body does feel complete. So that's how I felt right when we started. But then, as I'd experienced, using the hand and a little bit of success in some tasks, it did almost make me feel [complete], only temporarily, then once I'd stopped being in control of it, I'd lost an option for completing a task. Because I was able to do stuff with the hand like I've never been able to move anything with my left hand, even my gym prosthesis relies on me using my right hand to attach it to a bar and then it's good to go. But like that hand felt more able to perform tasks with me controlling it but not having to touch it.

R: What is it about being able to complete a task that makes your body feel more complete?

007: I think that it was like an extra option. I have one hand, [so] I have one option for doing things. Having the arm on gave me another option. Which, I guess, added to that feeling of being complete. I felt like because we had the sling on the forearm for quite a bit of that day. My right hand was out of action because it was supporting the sling, supporting the weight of the arm, but actually I was still able to be independent and do those tasks. Whereas if I ever had anything in my right hand and you said "hey, grab that tin for me". I'd have to put down whatever was in my right hand to grab the tin for you, whereas I was grabbing things with a left hand. I'd never done that before. It was less reliant on my right hand and actually having another option led to me feeling more complete.

R: Okay, there was another comment. You said a couple of minutes ago that you feel complete and then you said except for when you're doing sport. Do you feel less complete when you do sport?

007: Some sports. Yeah. So if I were to go to the gym right now and I didn't have my prosthetic arm with me, I would not enjoy that. I'd feel like I'd be limited in what I can do, and probably feel a little bit more self aware as well. Which is strange when I probably get looked at more when I have like this carbon fibre prosthetic arm on, but to me that is more normal, but actually to other people that's probably more interesting than just a guy with one arm in the gym. I think it a lot of it does come down to like the ability to do stuff. It's what leads me to feel complete or

not, so it's quite situational. Like if I was playing rugby, which I do. I don't wear my prosthetic for that because I don't need it. But if I was in the gym or riding my bike, I'd feel quite lost without the arm.

R: Thank you for sharing that. I wanted to ask you about the posture of the prosthesis. So for the statement "the posture of the prosthesis corresponds to that of a real hand", you consistently said you agree. But I am interested to know what would make it look more or less like the posture of it corresponds to that real hand?

007: I guess you don't always rest your hand with the fingers always open and the thumb in that [extended] position. So I guess that would make it feel or look even more like a real hand [in] the way the way it holds itself. And the way the fingers moved for the most part was very similar to how I would expect a hand to move, when it was grasping an object.

R: And what do you mean by that?

007: What I was especially impressed with is the way that if you were grabbing with a full fist grasp, but actually the object was smaller than the full width of the fingers then those other fingers would then continue to close independently whilst the other fingers had gripped the object and continued to squeeze it. Whereas like some prostheses that I've used before, those fingers haven't been independent of each other at all, and once you've gripped something with maybe even just the finger and the thumb, the other fingers will also stop as well, which looks quite unnatural cause a hand wouldn't ever really grab something like that.

R: Independent finger motion.

007: Yeah.

R: Interesting, thank you. Okay, now I'm going to get on to the control side of things. The next statement is "the prosthesis moves the way you want it to move". After the first stage, you said somewhat agree. The second stage you said agree and then after the third stage you said strongly agree. What was it about how you were using the prosthetic hands that made it feel like it moved more the way you wanted it to move?

007: So stage 1, it was that that tripod grip that was stopping me from agreeing more because I was doing what I thought was the muscle activation that we'd calibrated for it and it just wasn't doing it. But then as we went through the stages, I either became better at actually doing that or even later on in the study we didn't need that movement. So kind of a combination of, early on, frustration with that specific movement, but then later either getting better at it or not using it as much and that that made me feel like it was doing what I wanted it to more.

R: That makes sense. Similarly we had the next statement, which was "I'm in control of the prosthesis". So for this one again, you said, somewhat agree after stage 1. Then you said agree after

stage 2, but this time after stage 3 it stayed at just agree.

007: OK.

R: [Your response] didn't go to strongly agree like the other [statement]. This is slightly different. This is control the prosthesis versus the prosthesis moves the way you want it to move. Why do you think was?

007: Yeah, again, I think it's very similar for stage 1. As in, it would sometimes move in a way I didn't want it to move in, which led to me to feel out of control. Then I guess perhaps what has stopped me from saying strongly agree in stage 3 is that actually there were times where you were in control of the of the of the hand. Just because little bits needed doing to it [for calibration] or whatever, I think that probably disturbed my feeling of control at all times.

R: That makes sense.

007: And actually, the feeling of – and I've mentioned this already – the feedback on the arm when you were in control of it was quite strange. It felt like you were controlling a part of my body at that time. Which I guess would take away that feeling of control for me.

R: Yeah. I'm gonna come back to the feedback and that feeling because I'm really interested to your thoughts on it. The last one on the control section is "the movement of the prosthesis feels like an actual movement". After stage 1 you said agree, stage 2 was agree, and then stage 3 was strongly agree. Wha was it about the movement of the prosthesis that made it feel more or less like an actual movement?

007: Stage 1 and 2, I could see that that those movements were what you would use if it was on the end of your arm. Then stage 3, I was actually using it and it was working. So rather than just seeing those movements being useful, I was actually completing tasks with them and that made it feel that way.

R: So in stage 1 and 2 you were saying you could imagine it on the end of your arm?

007: I don't know if I was imagining it on the end of my arm, but what I could see were movements that I would use if it was on the end of my arm. Like grabbing something and turning, I could see how that would be useful. But then, especially when we were picking up those cans at the end, the heavy ones, the grab and the turn, it made a lot of sense when it was on the end of your arm and it worked really well.

R: Okay, so the first [stages] were kind of imagining how it could be useful?

007: Yeah.

R: And then when you're wearing it, it was being useful?

007: Yeah.

R: Okay. And what was it about that usefulness or functionality that made it feel specifically like an actual movement?

007: I think because it replicated the movement that I would do with my right hand. On all of those tasks... I have slid something with my finger and thumb off a desk before or I have picked something up and then turned it to look at it. Perhaps not turned it to be able to pick it up, but I picked it up and I turned it. So [the movements] were replicating movements that I do in day-to-day life.

R: I see. Okay now for feedback. This statement is “I felt a touch sensation in the prosthesis”. After stage 1 you said somewhat agree. Stage 2, you said agree, and after stage 3 you said strongly agree. What could you feel that made it feel like a touch sensation?

007: The squeeze on the upper arm and the intensity of that squeeze, depending on how hard I was trying to grip an object. But then as we went further, through the activities, I started to become more aware of how that corresponded to different gripping actions. I think I did okay on that identifying objects task, and that was where it started to become a little bit more natural. That was like I was able to feel stuff. Then especially in [stage] 3, I think because I’d had the arm on for quite a long time, by then I was getting a little bit more used to the whole feeling of it. That sensation of touch or feel became expected, whereas in the first part it was “ohh that’s like a weird feeling”. But I became more used to it and started to pick up a little bit more detail from that feeling.

R: Why do you think it became expected? Because I remember you said earlier that when you put it on, it was something that was expected, whereas on the desk it was something that was a bit weird.

007: Yeah, I think proximity again. The hand was attached to me at this point, which made it feel more logical that I would feel something from grasping an object with it, whereas when it was on the desk, I know I was connected by wires or whatever, but I wasn’t actually attached to the hand, so it kind of felt like I was feeling something that was over there, not near me.

R: That makes sense. I’m also interested – this is slightly separate to the touch sensation – when you were wearing it, could you feel that the end of the prosthesis would, say touched the table or contacted logged by the amount of like weight that was put on your arm?

007: That was harder, to be honest. I think I was well in tune with the feeling of squeezing an object, but something that I had particular difficulty with was knowing when the thumb had touched the edge of the table. Yeah, I did really struggle to feel that and even the perception of the length of the arm did make that a little difficult. Yeah, I did, however, feel more in tune with that sensation before I put the sling on, so in the very first task, moving the cubes from one

side to the other. There was that that [divider], I bumped that once or twice and I felt that, because it made the whole arm kind of move a little bit. And then when I was placing them on the other side, I could easily feel when the weight of the arm would have a bit too much, but for that one I could definitely feel it, yeah.

R: Okay so the next one is “I could feel the position of the prosthesis”. For this one, for all stages you said that you somewhat agree. How did you feel in relation to the position of the prosthesis?

007: Yeah, I found it harder to feel the position when it wasn’t grasping an object. I think if it was touching something I was getting more feedback through the through the band on my upper arm. Whereas in terms of position, I was relying very much on sight to approximate and see how many degrees I’d rotated the wrist in that position matching task, that was the way I was doing it, rather than feeling where I’d put it.

R: Aha, okay. The last statement about sensation is “you could feel the force being applied by the prosthesis” for this on you said agree, agree, and then strongly agree for stages 1, 2, and 3. I think we’ve touched on it a little bit already, but what was it that specifically made you feel like you could feel the force?

007: Yes, it was that kind of like total sensation of a squeeze on my upper arm. And I felt like I picked up on that really quickly and it just made sense to me. And then I think the reason it went to strongly agree was that I just had more time with it on and I was beginning to like build a picture in my head of what that level of squeeze meant in terms of the force that was being applied. That force matching task as well did help a little bit because I could see on the screen when we were having that first little play around with it, I could see what my output was versus the target but I think the reason it went to strongly at the end is because of the amount of time I had been wearing it.

R: Okay, so this this one is “I feel as if I’m looking directly at my own hand rather than at a prosthesis”. After stage 1 you said neutral. Then after stage 2 that went up to somewhat agree. Then after stage 3, you also said somewhat agree. Was it about the hand that made it feel more like you were looking at your own hand or not?

007: It definitely started at neutral because it was this big red hand on a desk and you could see some of the motors that are on it and the cables. But I very quickly realised that it’s more than that; I was in control of it. So that kind of balanced me out to go to go middle. Because it was unlike any prosthesis that I’ve used before, and I think as my familiarity with the prosthesis grew, it did make me feel like I was looking at more of a hand than a prosthesis. But, I couldn’t get past the fact that it was red and slightly bigger than my hand and yeah, had all these motors on the back of it and cables poking out of it. Yeah. So that’s what stopped me from putting strongly

agree.

R: Okay, that's Interesting. I mean, it is a big red hand made of plastic. I'm interested in stage 2 and stage 3 – you gave the same response. For other aspects of this, for example, for it belonging to you or it being your hand, you said that this proximity made it feel more like your hand. But what was interesting is this result in particular stayed the same. So I was wondering if you had any thoughts on that?

007: Yeah. So it's exactly that like it did, like the proximity made it feel more like my hand, but it didn't change the appearance of it, it was still exactly the same look.

R: Okay. So a lot of it's about aesthetics for that statement in particular.

007: Yeah, but that's not to say that I would want it to look anymore like a real hand like for me. I appreciate a prosthetic that that does a job, rather than looks like a biological hand. That's just never been what I've looked for in a prosthetic, cause I've had cosmetic limbs that have done very little in terms of practical tasks or helping me do anything in day-to-day life, and in actual fact [were] a bit more of a hindrance than anything else. But the prosthesis I have now and that I use all the time is like a black carbon fibre forearm with a titanium hook on it. It looks nothing like a hand. It looks nothing like an arm, but I still refer to it as like my arm. I don't expect it to look like a hand – I don't want it to.

R: Why don't you want it to [look like a hand]?

007: I'm not trying to hide the fact that I have one arm. What I want from something is to help me, and if it helps me and it needs to look... funky, then that's completely fine. If there was a hand that... actually no. Sorry, I was gonna say if there was a hand that was perfect and it looked like a real hand, I'd wear it. But I actually don't think I would. I think I'd rather it be clearly identifiable as a prosthetic hand because actually me having one arm is a big part of my identity and I wouldn't want to get rid of that, or have people unable to spot that.

R: Thanks for sharing that, I think it's really important for us to capture that.

007: Yeah, but like you see it with a lot of a lot of leg amputees. Very few prosthetic legs that I see people wearing day-to-day look like a biological limb, and loads of people wear shorts with them because [they] don't try to hide anything. In actual fact, that sometimes it's almost a bit of like, "hey, look, I cool my leg or my arm is", rather than trying to mask the fact that they are using a prosthetic limb.

R: Yeah. I would like to ask is there anything we haven't talked about yet that you would like to talk about?

007: I don't think so other than I really enjoyed the whole experience and the challenge cause it was difficult at times, but I really enjoyed that aspect as well. I found it really fun and exciting to

be able to use a bit of tech. It's really fun. I enjoyed it and yeah, exciting.

Participant 008

R: Okay, so the first thing I [want to] talk about or I want to ask you about is. We had this question. The statement that we asked you, which was “the prosthesis is my hand”.

008: Yeah. Yes, I do.

R: And with that one, before you started, so in stage 0. You had it down as neutral. Then after stage 1 that went up to somewhat agree. Then after stage 2, right down to disagree. And then stage 3, it went up to agree. So, it went all the way up again. I just wanted to sort of understand that bit more. Would you be able to tell us a bit more about it?

008: So remind me again, what stage 1, stage 2, and stage 3. Was stage 2 the feeling?

R: It was, yes, the stage 2 was squeezing onto that tin can and then putting a blindfold on and identifying objects in the hand.

008: OK, so stage 1 I scored as I did because it's just getting used to it, and so I couldn't really get a sense of what it was I was supposed to be feeling if that makes sense. And yeah, as I said, just just trying to get used to it so it was a neutral comment because I didn't know what I was supposed to be feeling. Stage 2 I would have scored like that because I've got no sense of what's what so there's nothing to say. And then stage 3 I scored as I did because I was able to use the hand and connect with it slightly. In order to complete the tasks that I was given.

R: Okay, so I'm interested in stage 3. So, in stage 3 there you said that you were able to connect with it. And I was wondering if you could sort of elaborate a bit more on like how that's related to this feeling that this hand is your hand.

008: So, by thinking of a movement and an action in my head, I was able to send that to the hand. And in order to do the movements and pick up the pieces so you have a connection with it, because I'm telling it to do something and it's doing it. So, I feel that I do have a connection with the hand and that I'm able to use it as if it were my hand. If that doesn't make sense, is that answered that?

R: Yeah I can. I can see that so it's sort of – correct me if I'm wrong – it's a sort of like this feeling that you can control the hand sort of makes it feel more like it's your own.

008: Yeah, yeah.

R: Okay, and so for stage 2, would you say that? Well, what was happening? What was happening there?

008: So stage 2 with trying to feel it, you know, and you took my eyes away from me. I can't, obviously I am. I'm able to move the hand by using my sight, but once you took that away from me. I have no sense of what I've got in the hand, so I don't feel it so it doesn't feel part of me.

I'm seeing with my eyes when I'm moving the hand and doing the tasks, but when it comes to actually touch and sense I didn't have a lot of it. I was guessing that's why I scored so low. So I've got no association with the hand no matter what I was trying to do and think of thinking my head. I was just guessing so and the scores show that. I didn't have a clue what I had in the hands, so. Unless of course it was a tuna can. Ohh the bleach bottle.

R: So the one that made sound.

008: Yes, I'm using my other senses. In order cause that's how I adapt, I use something else and my sight and my ears is what I was using to try and guess. But yeah, when you take my vision away from me, I didn't have a clue hence why I don't feel connected with the hand and I didn't feel it was with me or mine.

R: Gotcha. OK so I'm [going to] draw your attention now to couple other statements. Statement 13 "I am in control of the prosthesis". So I just wanted to understand that bit more about this sense of control of the hands cause what's interesting is on stage 1 and 2. So after position matching and then after this feeling [stage] you said that you actually somewhat agree that you were in control of the prosthesis. So [after] stage 2 your feeling that you could control it didn't actually drop. So I was just wondering if you could explain a bit more so when you were doing that blindfold test, did you still feel like you could control the hand?

008: No, because I couldn't see it. So I find that in order for me to tune in to control that hand, I need to look at it and feel that that hand is mine and sort of send the message from my brain to that hand to say, right? These are the movements that we need to do, and that's I use my vision to do that. So that's why then when we started doing the picking the penny up and the and the paper clip. Because I was able to see. Okay, I need to be able to use this much. You know precision and I'm using my eyes and feeding that back through the movement, so that's how I was able to connect with it.

R: OK so this feeling of control. Stage 3 was all about doing tasks with [the prosthesis]. Would you say that that had an effect on your feeling of control?

008: Yeah, I felt like I was able to control that hand and I felt like I had a good level of control because I was able to instead of just being robotic and I was able to precisely [external interruption]. And yes, so I was able to control the hand as was needed and so I felt it was. I was connected to it and it was part of me because I was able to give such level certain precision to be able to pick that up cause it I mean it was difficult. It wasn't without difficulty, but I was able to do it and I don't think that if you didn't feel attached or it part of you, you wouldn't be able to do that.

R: Interesting. Okay, so it's perhaps it's kind of tied to being able to see you doing things with it.

008: Yes, you're I'm getting the feedback from OK, so if I move too fast or if I think of the action too fast. It doesn't work, so I have to give. I'm relying on the feedback from my eyes to be more gentle, you know. And then obviously listening to your instruction and just trying to then relay that from my brain through my eyes into the hand. So yeah, I do have a connection with it.

R: Okay, interesting. Yeah, so I'm just gonna ask you about three statements this [time]. One is "I could feel a touch sensation", one is "I could feel the position", and one is "I could feel the force being applied". And after stage 1 where we asked you to move the hand to a certain position, you said you disagree. You disagreed with all those statements actually. And I [want to] start off by just asking you sort of what was making you feel that way.

008: I disagree? Sorry, can you repeat that? So I disagreed with...

R: You could "feel a touch sensation in the prosthesis". You could "feel the position of the prosthesis" and you could "feel the force being applied by the prosthesis".

008: Yeah, no, I couldn't feel anything.

008: In terms of like what I could sense, if I wasn't looking, I wouldn't know. I could only guess. So, say for instance if I wasn't looking at the hand and I went to make the movements. Then I wouldn't know if I was being successful or not unless I could look at it so in. So that's why I'm not feeling it.

R: Yeah.

008: Like in my body, through my sensory sort of you know I'm not getting no sensory feedback from it. That doesn't make sense.

R: In that case I'm then going to ask you about after stage 2. Where actually said you somewhat agree with each of these.

008: This is when I could see was it?

R: No, stage 2 is when you couldn't see. So, after stage 2 you actually said these actually increased. And I remember you saying at the time that you were feeling sort of like a tingling in your hand. And I want to understand a little bit more about that and what that was.

008: So, I think as it went on and I started to tune into it a little bit more. I don't know if – see it's really hard to say whether I was actually feeling it. Or what it was I was feeling because there was tingling. Like now, when I think about my hand, I'm feeling a tingle in my hand that's no longer there, so I don't know if I scored that way because I have. I know what the task is. I know what I've got to do. And so am I pushing that into the hand and making it tingle. I don't know, hang on, I'm going into a rabbit hole here. Half of it is I don't know if I'm really feeling it or if I'm willing myself to feel it so. I want sort of. I don't know [I was] making it up almost.

Does that make any sense?

R: That does. It's. It's an interesting mix of like wanting to feel something in the hand and [actually] feeling something in the hand.

008: Yeah, cause it's like you know they say, "you asked for the universe for something to come back and it comes back" like that sort of stuff. So, am I sitting there thinking "yes, I've gotta concentrate" so is that a sensation? Am I overthinking it and thinking yeah, it's happening or is it really happening so it's hard to try and distinguish between reality is it really happening or am I cause your brain's strong? Am I really wanting it to happen? So, I'm thinking that it's happening. That's like mind blown, but so I think sometimes I can get a sense of something's going on and you'll get different tingling sensations. But I don't know if that's just the way the injury is, and the message is going through. I don't know. Sorry, thank you.

R: No that's alright. Please don't apologise.

008: As clear as mud.

R: No, all of that made sense to me, at least.

008: Yeah, it's it's hard to try and express it because. You want it. I want it to. I wanna feel it I wanna do it so much that sometimes I think am I just imagining it like you know you just you tell yourself that and then that's what it is. But in reality, it's something totally different so I find it hard to distinguish between that. But I definitely did feel like a flicker or a flutter. But what it was, I don't know. It's like when I. The only way I can maybe explain it is when I get the nerve pain so my brain thinks move hand. And because the hand's not there it comes through as a pain because the messages are mixed up, I don't know so was I trying to think "yeah I can feel that" so there's a little flicker there [is that] my wanting it or is it actually happening?

R: So, to put that in kind of like a scientific way. It would be to say something like it's eliciting a sensation in the phantom limb.

008: Yeah, yeah, I'm willing it to happen, but how do you distinguish that it's actually happening? Or is it just that I'm telling myself that it's happening? Is it an illusion that I've created because I want it?

R: And just to understand a little bit more about why that might be happening. You had some reconstructive surgery on your nerves?

008: Yes, so they've done nerve and muscle transplants from my legs into they put it up into the chest and for it to then grow so [targeted muscle reinnervation] to connect with any of the nerves that were OK in the brachial plexus for it to then grow down to the stump, hopefully to try and help alleviate pain and then so then [the doctor] said that "you know these things take a while to grow", so could it have been that I was thinking? This is a movement, and that little

fluttering was the nerve endings being there. So it could be that it is actually physical and not me imagining it. Because I've had so many surgeries to try and reconstruct, it could be that it's a slight flicker and I'm then just adding on to that with my imagination.

R: Interesting so you may have felt some sort of sensation.

008: Yeah.

R: But identifying what object it was out of the question?

008: Yeah.

R: Okay, I'm gonna ask you about another one. This one, the statement is "my body feels complete".

So this is a really interesting question. This is the sense of completeness and what it means to you as a participant. At the beginning, before we started at all you said you agree. And then we did session 1 [which] was moving it to a position and it went down a little bit to somewhat agree. And then we did session 2, which is the feeling one and it went right down to disagree. And then when you used the hand [in session 3], it went back up to somewhat agree. So, I was just wondering if you could elaborate on any of that.

008: This was when I was moving it and it and that it felt part of me, yeah.

R: So this is your body feels complete. This sense of completeness.

008: So when I was moving the hand slightly. You do have a sense of you are complete. Very slightly because I've got an association with it and I can whatever I'm pushing from my brain is causing that to move. So yeah, and then it does make you feel like you have two working hands again. And then, but then obviously when it come to sensing, I can't feel anything. There's no appendage there, so that's why the scores went down and then back to when I was able to move the hand. Yeah, I suppose you do feel slightly complete because you've got two working hands again. I've not answered that.

R: You've done great. I just wanna poke a little bit more at it to do with this. So when you had the blindfold on so it was, you know I'm interested about this. Sort of like this visual connection between you and the hands. Would you explain a little more; so you're saying like when you've got it on you it feels like you've got two working hands again?

008: Yeah, yeah. So when I've got the hand on and I can see it because whatever movement I'm thinking it's causing that hand to move so that in in a in a way it feels like it's part of me because I'm controlling it so it's me that's doing it. And then when I when I can't see, I can't sense it. I don't know that it's there, so I have no control so I don't feel like it's part of me and then back to when I can see, and I was doing. The more the tasks that demanded more dexterity. Because I was able to control it in such a way, yes, it did feel like it was part of me. So, it completes you. If you know what I mean without sounding a little bit, you know. Yeah,

so it does feel like it's part of you.

R: I'm interested as well. In stage 1 you were controlling it and you could see it, but it wasn't on your body, it was on the desk, whereas in stage 3 it was on your body, but both of these have the same completeness score, so I was interested in hearing a bit more about your thoughts on that.

008: I think that's because I've got no. I don't know. I've got no sense of touch on the stump, so it wouldn't matter if it was on me or not on me. The fact that I'm controlling it is why those scores are similar is because I can see that I can move it, whether that be on the desk or on my body. So I feel like I've got a connection with it.

R: Gotcha. I'm gonna probe a little more on this – I don't wanna be too annoying with it – but so that you this feeling of control and this connection feeling, why do you think that relates to making your body feel complete?

008: Because I have the ability to move something and do what I need to do and so it's more helpful to me and so. I don't know if I would feel I like, say, for instance, in an ideal world I get the hand and I'm able to use the hand, so I would feel that I'm more independent because I can move this hand. Does that make sense? You wouldn't have to ask for help, because I can do it myself so that that's the sense that I feel that you would feel complete, because if I was at home, wouldn't have to ask anybody to help me cause that sort of makes you feel a little bit more complete does that.

R: Okay, so this idea of being independent.

008: Yeah.

R: I'm going to probe it again on that. What do you think it is about being feeling like you could be independent that makes you feel complete.

008: Because if you're on your own and you're stuck. Uh, and the one that I'll bring it to what I relate to the most is food preparation and if I'm on my own and you know I haven't got my mum or dad there. If I had that hand there and I'm able to grip with that hand to open, then I don't have to ask anybody or I don't have to go. Ohh I can't do that because I'm unable to open it, you know and it's them little things that really frustrate me and calls me such annoyance. And when it “****es me off” is the best word to say, because I can't do it myself and I used to be able to do it myself so to have something that goes actually I don't have to ask anybody because I am fiercely independent and I could open it. It makes you feel complete because you can go about your, you know on your own without having to ask anybody and you don't feel weak. You know that's my big hang up like a feeling weak because I can't do it and I have to ask for help. You know, you do have to, I will ask, but I just don't like it cause it I just wanna

get on with it instead of having to you feel like you're being a burden, you know.

R: Thank you for that. That was a lot of information, I appreciate it a lot.

008: No problem.

R: I wanted to ask a little bit about this question which says "the prosthesis is in the location you'd expect your hand to be in".

008: Yeah.

R: And so, when you wore it, I just wanted to know a bit more about. What did you expect, like where do you expect your hand to be sort of? How does that line up? What goes on when you think about "this is where my hand should be"?

008: I'm so when I had it attached to me. I felt that it was the right length. As to where I would expect it to be, because if it if it wasn't where I would expect it to be, then I wouldn't have been able to control it as I did, because if it was too long or not where I want it, yeah, as I said, I wouldn't. I wouldn't be able to be able to move it and work with it to do what I wanted to do. If I didn't feel like I had that connection. So that's why I answered that way.

R: Thank you. There are a few questions we asked you also about, so it's frustration and sort of physical demand and stuff like that. I'm going to ask you first about frustration. So, in the first, the first session where you are moving it to positions, you said the frustration was really low, at 15%.

008: Yeah.

R: Like 15% and when you put the blindfold on your frustration when up to 80%. And then when you were using it to do pick and place tasks, it was about 50%. So I was just wondering about each of those tasks what it was that made you answer in that way.

008: Okay, so the first task, because it was an easier movement to do and I felt like I'd sussed that movement. You know I didn't feel that I was struggling too much with that. The second task is I couldn't feel it, I couldn't see it and it's really it's annoying cause I wanna succeed and I wanna be able to do it and I can't. So that's why it shot up. And then the last one I knew I was doing it and I was capable of doing it, but I was giving myself [pressure]. It was the point of giving myself time to try and be as precise as possible and slow it down a little bit and then what happens is you're dealing with the fatigue at that stage. So you're trying your best to do it, and your body's not sort of doing what your brain wants it to do. Um, so that's why the frustration got a little bit. I'm tenacious, I don't give up, so I was determined that I was gonna do it. But yeah, the frustration is high, but purely because I know at some point in my life, I've been able to do it with no problem at all and in my head I've still got it hard wired. I should be able to do this, but you know, as you said I had what just a few hours session testing with

that. If I had the you know if I didn't have to work or what not and I could just practise and train then. I know that I would be able to use that efficiently and that and that's the massive difference. If we were given the care and the time to practise and use these things, then more people would use their prosthetics because they know how to.

R: There's a lot that, okay, so a lot of factors go into that. I'm gonna try and do each one by itself. I think the first one you mentioned was that you felt some fatigue.

008: Yeah.

R: And that was kind of making you feel frustrated. What about fatigue Is it that makes it more frustrating?

008: Because the must, I think the part is you're tired so you know what you wanna do, but it's just trying to get your body to do it. A lot of where I've had muscle transplants and the muscles have muscular atrophy. The muscles are weak. It's not as strong as it could be, but I know that I can build that muscle to be stronger, but I'm just not there. I'm just impatient that's my personality, which isn't a bad thing cause it pushes me to do what I've got to do. So I think in terms of the fatigue it was about giving myself the time to be able to do the task or just take a breather. You know, sometimes I find myself and holding my breath it's not helpful.

R: OK, the next thing you mentioned was how you had this reference that you could do it before, and that you want to be able to do it now and it's frustrating.

008: Yes, so you know I went 22 years with 2 hands and I was able to. You have the dexterity you can just do things without thinking about it. Then it's taken away with me for like 23 years. So you then become adept to using just the one hand, and then when you go and start to use 2 hands again, you're just you're switching your brain back and your brain, then I don't know if it's muscle memory or what it goes back to "Ohh I'm 22 again. I've got 2 hands", but it's not the same, so it's [about] trying to tell yourself, "OK, there's something there, but it's not the same" and it's trying to give yourself time to learn that, so that's what I meant by that.

R: And what about that made it frustrating?

008: Because I thought I should be able to do it, I don't give myself the time. I thought I should be able to. I thought like everything I approach; I think "I should go in and smash that, I should be able to do it", but it's not. No marathon runner went in and did 3:30 did they? You know, they practised, they practised, but I'm very impatient and I just wanna do it and succeed and so I'm not giving myself the time. I wanna go from A-Z as quickly as possible without doing whatever it needed in between. It doesn't work like that. Well I still try anyway, even at the age of 45, I've not learnt this. So if I can work on that sort of thing. That's a brain remap that one.

R: Interesting. Okay, now there was one where we asked you about temporal demand. So we asked you about how hurried or rushed he felt while doing the test on all three tasks you put down roughly the same. So, I think you put 70 for the first 2 and then when you're wearing it you went up to 80.

008: Yeah. I think because I know what it's capable of but I wanna do it so badly that I'm not giving myself the time to do it and so I'm like come on and then you get frustrated and then you can't think. So that's when you know you need to take a step back and just try and calm, but that's me. That's something that I need to work on and going forward for me to get these [prostheses], I need to realise it's gonna take time. I'm not gonna be able to put it on and be really like fluent with it like it's my organic hand and that's that's difficult. And because I've been working so hard to try and get this hand, I think "ohh, I should be able to use it", but it doesn't work like that. And that's why I think. [external interruption] Yes, so I've been working hard to get the hand that what I you know when I eventually get it, I need to understand I have to give myself time what with it. So even though you've got the hand, it's like right, this is gonna take a while. You know the journey hasn't finished. Cause you've got to now teach yourself you've got 2 hands and they got work together and so that you know what you were saying about and the statistics showing that [often] people that do have [prostheses] don't really use them, and it's because you need that sort of care and assistance in the middle to show you how to do it and the time that it takes, and to be able to give yourself time to use it properly. So I think that if there was some sort of treatment or programme where people do get their prosthesis to sort of hold their hand, pardon the pun to show them how to use it. More so it wouldn't be wasted.

R: Okay, so it's this this thought about after care?

008: Yeah definitely, because that's the thing and the first surgeon when I was with [the hospital] where my accident first happened and when I found out about prosthetics and I went to [the doctor] and I said "what about a [prosthesis]" and they went "ohh no you'll just get bored and leave it in the drawer" and I was just like "well no I won't" but that's actually got a bit of truth [to it]. I suspect that's what people do cause they gets so frustrated they can't use it like they would think that they would use it. You know then they need that support package to go right? OK, we do little bit by little bit hour by hour. You're not gonna just put it on wear it all day and be able to do everything you used to do cause that's what I would want but you can't.

R: That's really that's really interesting to hear from my perspective as well. Thank you for that.

008: Purely because I know that I would feel I'd be like, well, why can't I do it now? You know I should be able to play the piano like I'm going to the extremes, but it doesn't work like that. It's not to replace your hand that says to assist you cause you'll never be the IT will never be as good as what you're born with.

R: Okay, I'm just gonna ask are there any other sources of frustration or anything that you wanted to talk about or bring up?

008: I think I find that because I get the excruciating nerve and phantom limb pain. I find that there's a lot of factors there that make that worse. If I'm tired, if I'm stressed, then all adds to your frustration and I think you have to be [aware]. When I get this [future prosthesis], I have to be really aware of that, because if I've had a really crap night's sleep and I've been in a lot of pain, you know it's not gonna go as planned. I think that a holistic approach is what will be [important]. But I also find that when I am training brain training doing me the hand, I get no pain. So there's definitely a connection that using a prosthetic limb correctly can help alleviate or not make the pain [worse]. I mean, you get the odd spurt, but like you know I've been paying for. I've been paying for a couple of days. Because you tend to sort of not use the [affected] arm or whatever, I started to imagine doing stuff. It's like the brain thinks "ohh there's something there". And so it helps reduce the intensity of the pain if that makes sense.

R: Understood. Say with this pain. Did you have much pain while doing the study?

008: No, I didn't. I find any studies that I've done, any brain training that I've done that I may just get one sort of 'rogue pain' come through, but it's not like you know if the weather's crap. If I'm tired, it's like in the background of this [interview]. This this gripping burning pain, but I got none of it so. There's definitely a correlation between using prosthetics and like the phantom limb pain.

R: Really interesting.

008: I would rather feel that then be exhausted from that gripping pain all the time because it gets bad and adds to my frustration. I'm incredibly lucky I don't get depressed. I'm not anxious, just get mad. Which probably isn't a good thing, but that's why I use sport. But then by distracting myself and doing another thing that helps. So, I think all of these is not just one thing. It's not "I'll get a prosthesis and all of your all of answers [are there]", there needs to be a complete package. There's these things that go on [beyond fitting] you know, you need to cater for these things and needs to be a whole programme of understanding from professionals, researchers like yourself, and patients to say "okay, these are what you feeling. This is totally normal" and just being able to manage and know what to expect really because everybody's different. I reckon that everybody will at some point experience some of these feelings and they will be able to tick at least a handful of those boxes. There's, you know, there's a similarity with everybody.

R: It's lovely to hear to hear your thoughts. I'm going to ask you, this is touching on some of your previous experience with prosthetics. Particularly [that] you've tried a few myoelectric hands and I'm interested to hear your comparison or your thoughts on what we did versus other hands

that you've used.

008: So, uh, I have done a trial of the i-Limb. I've also tried the bebionic. With both of those, they are quite – so that i-Limb is, I mean, it's lovely. It looks good, it moves quite well, but it's still very robotic. It doesn't flow, and it was quite fussy. It's nice having the app, but I felt like it was more of a gimmick. It's not something I would put on and [think] “okay, I'm going to do this task; I'm cooking a meal”, it's not something I would be able to pick up. I want it to be more basic and have the important things like the infrastructure there. It's also quite heavy. The bebionic hand feels more sturdy. It's a lot more user friendly as it was a lot more simple, but still really very heavy. The hand that you had created. And I felt that was a little was a lot lighter, but it would be because it was made out of 3D plastic, but I suppose, you know? I don't know what [material] you would use if it did go into manufacture. You have to use metal, or you know that would be something that you would have to do. But that it was a little bit more... it was less jerky. I have that precision. I could pick up the blocks when I'm using the i-Limb. I was doing it, but it was it wasn't as easy as I as the one that we tried last week.

R: I'm interested – at the end there you said that you found it a bit easier to use the one last week. What in particular you might mean by that?

008: So when it came to the finer motion. The picking the pennies up. Because the action felt smoother, I felt I could control it more than if was jerky. When I had the other 2 limbs, I had them for a week or so to practise with and you would do a little bit of practise, whereas when I did your one we had what just a few hours and I was able to move that. And you know progress on to moving smaller items because I felt that the action was a lot smoother. And me thinking of that action was sort of transported or moved into the hand in a smoother movement, whereas if it was jerky, I would never have been able to do it. I think that because of 1) the weight of the bebionic and i-Limb, and 2) the jerkiness and the very stiff movements. That's the reason why it was easier to move your hand. More fluid. That's the word, 'fluid'.

R: I just want to touch on one more statement before we head towards the end of this interview. It's this statement that says “the movement of the prosthesis feels like an actual movement”. For all of the tasks where you were using it, you said agree. With the blindfold [stage 2], it was somewhat agree, but still positive. I just wanted to understand a bit more about what, what an “actual movement” feels like to you?

008: Well, it's a lot smoother. It's not a jerky movement. So when I would control it instead of it going like that [imitates a jerky movement], it was [imitates a smooth motion]. In the real world that makes sense, which is what you need, you don't wanna be able to crush something to death. And like when I was. With some of the hands that I was [trialling previously] with [the prosthetist], I don't know why I did, but I put it to my neck and the hand actually just

closed on it. And then I'm thinking "****". You know, it's probably [beneficial] to idiots like me to have something a little bit smoother so that you can sort of get out of it instead of a jerky movement. So yeah, that's the only way I can explain that. I felt that had I put hands around my neck I would have been safer. Not that I would [put the hand around my neck]. And it's not a jerky movement. It felt a lot smoother. And so yeah, you feel more of an association of and that moves a little bit more like your own hand.

R: Is [there a] relationship between it being smooth and it feeling like an actual movement?

008: Yeah.

R: What exactly do you mean by smooth motion? Relating it to your own hand?

008: Well. If you had a jerky [movement]. You wouldn't be able to control it as well. So, like your own hands, sometimes you need to be gentle with things in order to pick them up, and to know whether it's a glass or know whether it's something soft or holding like human's hand. It's how you're delicate. So if the hand is smoother you have more of a connection with that hand, because it feels more human. You would be able to relate more to it. Does that make sense? If it was jerky and like sort of [C3PO – a fictional robot], you don't feel connected to it, whereas if it's a little bit smoother and mimics more like a human hand, you feel more of a connection to it.

R: Just to clarify: smoother as a word could mean just moving between jerky positions in a really smooth way.

008: It's more of 1 [continuous] movement as opposed to lots of 1234 [fixed movements]. You can go from one action to another action. When I was picking the pennies up I was able to sort of move the hand like that [smoothly] and I feel that with the other hands I've tried, it's more open, close, open, close. More fluid, maybe more, more organic, it felt more organic.

R: Okay, the so the way we describe moving between these fixed positions is called discrete control.

008: OK.

R: And the way we have this continuous motion is called continuous control. Is that what you're referencing, this sort of ability to have this continuous motion?

008: Yeah, because you're not having to switch. I'm not having to switch from right move this bit [of the hand] to move [this bit of the hand sequentially]. I have to think of 2 different actions in order to move the hand the way that I wanted it to, but where you've got that continuous [motion] it's easier to control the hand than being in jerky movements.

R: Thank you very much. My final question to you is an open question. Is there anything that we haven't talked about yet that you would like to bring up or talk about?

008: No, I don't think so. I'm trying to be part of [research] and to see what's going on in the background cause [as an amputee] you don't see what's happening. I find it's just reassuring to know that maybe not in my lifetime, but maybe in someone else's it could be possible that actually, you know you lost your limb. Yeah, it's ****. But you know, we've got one which you'll be able to be as independent as possible. I've just really enjoyed being part of it. It's nice to sort of help out and give my feedback.

Participant 009

R: The first one I want to ask you about is the statement which was “the movement of the prosthesis feels like an actual movement”. At the beginning, that was strongly disagree, before you’d used it. Then after you’ve done the position matching, moving the hands to set position shown by those green bars, that went up to somewhat agree. Then after we did the force matching, so grabbing hold of that can with a specific force, then putting a blindfold on and identifying objects that went up to strongly agree. After the final stage where you wore the hand and you did some pick and place tasks, it stayed at strongly agree. So what I wanted to ask you about is what was in your mind, what was happening during those stages to make it feel like an actual movement or not?

009: In the first part I think I was getting used to it but by the end I could actually feel the muscles on my arm moving. So every time I felt the muscles in my arms like hiding in certain muscles, I can actually feel the [prosthesis] moving. So in a way it did feel like it’s part of me, like I can control it with my arm with the same movement in my arms. I could just control it. So, to me, it started getting closer to actually feeling like the movement in my arm and feeling like part of me. I can control it and it takes a lot of focus as well, it took a lot of energy mentally to move the hand so it did feel a lot closer, like I can control it so it kind of felt a lot more like a part of me.

R: You were saying there that it feels closer to you. What do you mean by that?

009: It’s like... I’ve got a [different] prosthetic hand and can’t move it, but with this one I can move it and therefore it, as I said, it takes a lot of energy. So I have to learn to control the different types of [movements], and at the same time, the muscle is just learning to find out how much pressure and how much force to put into my arm to control the fingers. It did take a lot of energy, so it did feel more like [part of me]. It’s partly because I had to try and control the fingers and eventually we could feel the fingers as well. But yeah, I felt closer [to the prosthesis] because I had to control it.

R: Okay, and what about that made it feel like an actual movement?

009: To have to use my movement and then I can control this [prosthesis]. It just felt closer to that experience. It wasn’t too... it’s not like obviously I can do this [moves individual fingers of their right hand]. It’s more [like the relationship between] more force and more tension and more focused to do it. It’s different, but it’s a new experience that kind of also feels a lot like [my right hand]. [It’s like if] you were picking up a weight and you lifting a heavy weight. You get that force and you’re lifting it but you can that feel as the muscle straining. That’s what it felt like when using [the prosthetic hand]. I felt like I was building muscle. Yeah, it felt more like

[an actual movement] because you can [relate it to] when you're doing weight [training] you can lift something the same way. That's what it felt like; my arms training the muscles. The more tense you get, the more it moved, so I had to try and figure out how much force to put in it. Like you would do weights, it's a new type of weight [in a] way. The more you want to close the fingers to pick up something, the more pressure, the more strength you have to use and it felt like it's gonna build the muscle like in the gym, and that's why it felt like me. That's why it's felt like closer to being an arm, because when you're picking up the weights and you lifting it and you can feel this training, that's what I found with my arm like it felt like I'm building the muscles. The more I have to focus to be able to use the arms. What because the muscles that are in my arms [were] starting to tire out, so I had to learn to control it at different times. At the beginning my arm was relaxed – it's chill – and then at the end it's like tired and exhausted and you get this lactic in the arm as well. So you it feels like the gym kind of picking up something in the gym.

R: I'm OK, the next one I'm going ask you about is that statement that says "I am in control of the prosthesis". After stage one, so after the position matching, you said somewhat agree. After stage two, so after you were grasping the can with some force and then you put a blindfold on with the object detection, you said you strongly agree. But then after stage three, where you had worn the arm and you'd done these pick and place tasks, it went down to somewhat agree again. I'm really interested in that [change]. What happened between stages 2 and 3 there?

009: Stage 2 okay, I felt I enjoyed that because I can actually feel what pressure I'm placing on the certain objects and it had the feeling of when you closing it, different parts of your arms had hard pressure on it so it didn't take me long to figure out which object was [associated] with which amount of strength and which pressure. I could identify [objects] like... this object is more pressure on my left part of my arm or my right part of my arm, or it connects to all around my arm. I think it was the can or something. The screwdriver it had a sharp pressure around my arm. It wasn't too discomforting it's like just like a shock to let you know that it's picking up an object that's smaller, but if you require more strength [it applies] more pressure on like my arm. So after a while I could identify which object I'm holding because of the way it triggered in different parts of my arm. Like after that it did feel a lot like I was in control of it and it did feel part of me as well because I could identify which I'm object I'm using. What exactly was the question?

R: So you said you strongly agree to "you're in control of the prosthesis". When you then went on to the next part where you wore the prosthetic hand and then you did the picking up the small objects, stacking the checkers, doing the blocks in the boxes, it went down to somewhat agree.

009: Yeah, that one is because even though I picked something up, I had tensed my muscles, once I

tensed it I sometimes let go and I don't realise I let them go. In my arm I [paid less] attention [to the muscles] and then I might just slightly open up [the prosthesis]. And then once I did that it drops the object. So, in that way it did feel like I wasn't so much in control, but I had to learn how to maintain pressure I'm using in my arm and holding that pressure even though I was tired. I did it for a long day and so the tiredness would made it so that I couldn't control how much pressure exactly what I'm putting in and therefore I wasn't totally in control of it. I think it didn't feel as much like I had control of it or not enough experiment.

R: Understood. The next statement is "the prosthesis is in the location where you would expect your hand to be". And you said in stage 3, so when you wore it, you said you strongly agree. And yeah, I was just wondering what did you think about how the prosthesis lined up to where you would expect your hand to be?

009: I expect my other hand to be at the same place. I haven't actually put it together to find out if they actually same length. Yeah it may be slightly longer. I felt like it if I had a second hand, it would be around the same place.

R: Okay. I'm interested in this statement that says "my body feels complete". Before the study, you said strongly agree. Then, for the rest of the study, so once you started using the prosthetic hand, you said disagree.

009: Now, my body feels complete like this way. I do feel that prosthetic arm, if I had it, if it gets more advantages, it would be something that I would use for daily use. It is something that can help if I were to pick up certain objects, see if I held something small in [my right hand], and then I need to hold something else, that would be something it would be useful [for]. But yeah, I would say I feel complete now. However, with the prosthetic hand that would be something that could advance certain aspects of my life. I would say it will help build the muscle in my left arm, which would be awesome for the gym, you know.

R: So during the study you said that when you were using it, your body didn't feel complete, so you disagreed.

009: That would be because, even though I had control of it, I didn't have total control of it. It's like there were still aspects that I couldn't control, and the experimentation is good, it's great, but I just didn't have so much control of the arm as I would like it to have. Like, imagine if I can move, the [individual] fingers [that] would be cool. At the moment I can control it, but I didn't feel like I was [complete]. I don't need it [to] feel complete.

R: Just then you said you didn't have quite as much control over it as you would have liked and you would have liked to have moved the individual fingers. What about that would have made you feel complete?

009: With a left hand, I find maybe I don't need to use the fingers. We did use the opening and closing, that was good when picking up certain objects which would be good if I was to hold something and pick up something else. If I was to move the fingers and had that kind of control, that would be awesome, but I don't know how that would be possible yet. At the moment there's a stage where we were picking up objects I felt. Yeah, I could pick up some things, but I don't know how, if I was to use it, would I be able to pick up something that's heavier? Where [a prosthetic hand] would completely help me, or whether, actually, will I be doing as I am now? I am so used [life without a prosthesis]. I can do what I can do now, and I can do more stuff with my arm now [than with a prosthesis]. Like it's natural without with the other arm is not so natural in as well.

R: Okay, the next statement is "the prosthesis is my hand". In the beginning, you said strongly disagree; you hadn't used it yet. After the position matching, you said strongly disagree. After [stage 2], you said strongly disagree. Then after you wore the hand in the final stage and used it, it went up to neutral.

009: That's because, over time, I used it and it became... because I'm using the muscles again and I felt like the weights again, it did become closer to being my hand, like I had more control of it. And, to some extent, I felt like it was part of my arm because the amount of exercise in my arm. So therefore it felt like part of my arm, I have control of it. So yeah, it kind of felt like in the middle of [the study] yes, I did. I still didn't feel like sensation of the arm where I can touch it or and I feel the movement exactly but I can feel the movement in my arm when I tense in my arm itself. It did feel like my arm and I can feel the [prosthesis] on my arm, so it did feel it might not be exactly my arm [that can be] touched and I can feel the sensation but I did feel the [prosthesis] via the muscle movement in my arm if that makes sense.

R: Okay, so you when you were wearing it, you could feel it on your arm?

009: I could feel it on my arm and I can feel the muscles moving, so therefore I had control of it but as I think of [my right arm] now you can touch it and sense that and I can move it I can feel connected to it. With the prosthesis I can only feel what's on my arm at that moment, other than that I can't do anything about it. I have no sensation on the [prosthesis] so I can't feel the arm itself. I can feel the [prosthesis] being on my arm so I can feel part of it. The prosthetic hand being on my arm and I can feel the muscles being moved and controlling the hand, but I can't feel the actual hand itself as in touching it.

R: Ah okay, and a touch sensation would be quite important?

009: If you wanted to make it more like a hand, you would feel it. So say if you can touch your hand now, you can feel the sensation, then you know it's your hand. At this stage it's like I can feel

that the prosthesis is on my arm, but other than that you can't feel the external sensation of the hand. You only know your it's connected to you because you're controlling the fingers by the muscles [in my arm]. If you can have the touch like, say if you can touch it, I would say that will grow to become more like you, become closer to your hand.

R: Okay, and what about the haptic armband, what did you think about that?

009: It helped. The speed and the amount of pressure. You can control the muscles in the arm, but once got that around you and you can feel like I was saying about the pick up the cans and certain objects. You can sense what objects you're picking up even when you have the blindfold on. I could feel which object I'm picking because it is triggering different parts of the armband, so different parts of the band had some sensation where there's a poking here on the right or there's a poking on the left, or maybe it's all of the arm, or maybe it's like a clenching kind of feeling where you can something's holding on to your arm and then a poking. At some points it could be the poking on the left or the front so you get different associations, so you kind of know which objects you're picking up but. Yeah, I like that experiment. It's only when you tricked me when you had the same object three times in a row.

R: It's a randomly generated order. I'm gonna ask you about how mentally demanding? So the first stage, the position matching, you said it was 5% mentally demanding. The second stage you said 0%; not mentally demanding at all, and then the third stage where you were picking up the small objects, you said 0% again. I was wondering specifically about that middle stage with the blindfold. What was it about that that made it less mentally demanding?

009: First one, the positioning, didn't feel mentally demanding. Second parts of that when you talk about now, that is because it I could sense the object. And the hand was clenched on the object. I wasn't turning the hand, it was just clenching down. I use that muscle all the time, that clenching muscle, I use that myself quite often. If I was to pick up a bag of shopping, I use it to pick that up so that muscle didn't really take much energy or demand for me. Because I'm just picking up the object and just clenching down until I can feel the object and then I can feel the sensation on my arm with that band. So it didn't take much; it wasn't mentally demanding at that stage. The last stage, that's when I got tired, which I think the certain objects [that I picked up] were smaller and that is a lot of... it was hard. Picking [objects up off] the table is really difficult, you have to be so focused to pick up each object, that takes so much energy.

R: When you were talking just then, you said that the first stage wasn't that mentally demanding?

009: It wasn't when we had to learn to control to close and then turn it. Yeah, that that that stage was just practising the different levels of pressure I had to use. It didn't feel so demanding. It's more exciting.

R: You actually rated that one as the most mentally demanding.

009: I'm sure it wasn't that demanding. I would have thought [in hindsight] that the last one would be more demanding. At the end, yeah, picking up tiny things.

R: So mental demand, you said that you don't remember the first stage as being very mentally demanding, but at the time you said it was quite mentally demanding.

009: Maybe because I was not used to it. It might have been taking a lot more out of me from figuring out how much pressure, how much of that muscle I need to use. Maybe that's why I said it.

R: OK, we're going to look at physical demand now. You rated the first stage as pretty high, so that one you rated as 90 out of 100. The second stage was a lot lower at 20, and then the third stage you also rated low as well at 20.

009: The third stage, that was the most [physically] demanding. I think it would have been but I said no... why would I say no? Maybe I got used to the arm and that I can control it. I knew how much pressure [to apply with my muscles], that would make sense as to how it wasn't so demanding. The only thing is I used it for a couple of hours, and picking up objects [was difficult] too. I think we picked up the coins, and the cans – the cans were easier. I found that easier but the coins and the bottle caps I love. The bottle caps were easy to pick, that was awesome. I enjoyed that one.

R: Why was that awesome?

009: I don't know, it's like the hand just felt like... it was effortless. I could just pick [them] up. It felt like my arm is actually my arm and at that point it just felt like I knew what to do. It was like a sense of "I'll pick [the object] up and put it [in the can]". It was easy, but then the other thing was that the coins were more difficult. I had to change the hand angle then learn [that technique] too. If you had to pick off the table to move it, and then how much pressure you use, and then to not lose the pressure you put on to it, because if you do that then you drop the coin and then you have to go back and do it all again. I think some parts wouldn't be demanding, but that coin was a little bit demanding, would say then overall it's not demanding. I felt like a lot like the arm was part of me. It was effortless. The coins... I enjoyed it because I couldn't do it. I wanted to do it again until I found out how to do it. It was fun. It was definitely fun, because it was the only experiment that day, I think, that challenged me more. And because it challenged me, I thought "okay, I want to do this task", just to make sure I do it better than I did.

R: The ohh I've got two more that I want to ask you about. The first one is about performance. So this is what you thought about your performance, not the actual numbers themselves. So in the first stage you said 80 out of 100 – that's quite high. The second stage, after the blindfold, you

rated as 45 out of 100. Then the third stage you rated as 75 out of 100n.

009: The second stage, that is because I wasn't sure if I had it correct. I didn't know until afterwards. [Afterwards] I thought "ohh, that makes sense" because I can feel the motion and the pressure on my arm so I know which object I'm picking up, but at the time I was kind of confused. Especially when there were three [of the same] object in a row, I couldn't believe it. My expectation was that I didn't do as well for stage two. For [stage] one, I felt like I did well. I [could] checking easily, see what I'm doing and I was aware [that] the pressure [in my muscles] this rotated to this side or this much pressure to clench this side. That's why I felt I had a higher performance there and the third [stage], which was picking up some things, that was high. I was able to learn to figure how precisely I wanted to move the arm and when to grasp and learn to actually control it. It took a lot of attention to do it; a lot of effort to pick up something. I enjoyed it because it's like training; it's making my arms "jacked" and you get my arms tired. I felt better on that one because I [like] more of a challenge and I just kept wanting to do more to see how fast I can get it.

R: Okay, you could see yourself learning how to do these?

009: Think I could do it all effortlessly in the future. Especially if I could get a [prosthetic] arm, I would think everything would be easier, it would be automatic eventually knowing how much pressure I need to put in my arm and how much to let go at some points when I'm picking to unlock and drop something.

R: The last question I'm going to ask you about is frustration. You rated it as low as possible for the entire study.

009: Yeah, it wasn't frustrating. It's mentally demanding sometimes, but it wasn't frustrating. I enjoyed it – this is fun for me. It was never frustrating at all.

Participant 010

R: As a quick refresher of what we did, there were 3 stages to the study. The first one, stage 1 was matching positions with the prosthetic hand that was on the screen. We had the green bars and then we had some red bars that we were controlling them to get up to that level. Stage 2 was doing the same thing, but for a target force, so it was squeezing hold of a can and trying to match the force. Then putting a blindfold on and identifying objects in the hand. Stage 3 was wearing the hand and doing some tasks like moving the cubes from one box to another and picking and placing objects. Select picking up paper clips, the cans and the full cans, the heavy ones. We didn't do the paper clips because of the elbow of the socket not being present, so wouldn't have been able to get a suitable angle to make that task possible. But we did do stacking checkers. We did do flipping over pieces of paper and stuff like that. I'm going to ask you about a few of the things we talked about in the questionnaire that we filled in after each stage. We're going to start off with mental demand. For stage 1, with the position matching experiment you had that down as 15 out of 100. After stage 2, with the force matching in the blindfold that went up to 40 out of 100. Then for stage 3, that went up to 70 out of 100. I'm interested to know what you can remember about the mental demand side of using the prosthetic hand for each of these stages.

010: I think for the first one, I think it's because I haven't used any of the muscles or any of the impulses in that arm at all. Now I've got this [static prosthesis] on, I've been doing something outside with this [prosthesis] on and it is quite useful to me. But, I have to do everything [manually] with it. With [the myoelectric hand], I moved my arm and it moves. But when I'm asked to like grip something, I've got to think about it and that's where the mental demand comes in. To match the red bars to the green bars - I've actually got to think hard about it. For a few days afterwards [I felt] quite stiff because I've never like done anything like that for 3 1/2 years, and to do all that in one day was quite mentally taxing, physically taxing.

R: So having to think about moving the muscles in your arm to make the hand move was quite mentally demanding? On stage 3 where you were doing it with task when you were trying to complete tasks, did that make it more mentally demanding?

010: If we separated it into three separate days, with a bit of a break in between. Maybe it wouldn't have been so bad, but because we aimed to get it all done in one day, it was quite taxing. I mean, just not just physically, but just the thought of it just thinking about what I've done. Technically speaking, all I'd done is sit down all day and thought about what my arm's doing and making me hand do what I wanted it to do. I was tired. If I was using muscles on a daily basis they'd probably get quicker or looser. I can still [move my muscles] now; I can still think about it and do it now, but it feels sluggish because [I don't use them]. I don't know whether

they'd loosen up overtime or don't know. At the moment I can still move my thumb and my two index fingers... I can still move them quite freely but my ring finger and little finger are slower. Whether a more sensitive [electrode] could pick that up and activate a hand with all the nerves and the muscles.

R: Okay the next one I wanted to talk about is performance; how well you think you did at the task. For the position matching stage, you said 70 out of 100.

010: Is that is that the green bars and the red bars?

R: Yeah, that was the green bars and the red bars.

010: I think that doing it on that day cold. I don't think that I, personally, did too badly. I was getting the hang of it. With more use, I'd probably get better.

R: Then when we did the blindfold task with the objects, and performance was down at 35 out of 100.

010: I don't think it did that well on that one because everything happened on the one day. If I got the hand and took it home and got [used to] the feedback. But trying to it [with less practice] was a bit confusing for me. It was hard enough to get the that the hand to work and do what you wanted. Recognising like a can and getting the feedback and recognising how much feedback you get off that as opposed to the smaller objects like the squishy brick, that was tough for me.

R: Okay so it was made harder because you had to concentrate on how to move the hand and then it got more complicated because you were trying to figure out the feedback at the same time?

010: Yeah, it was hard enough. I mean, I was getting used to it. The more we did it, the more I got used to actually operating the arm. When we took a reference of the two fingers and the thumb, and then [another two references] moving the wrist up and down. Getting that to work with the hand... I was concentrating on doing that and then trying to recognise what feedback I get from individual items. That was the hard thing for me. If I could take the hand home use it a lot, I'd get used to what feedback there was. But on that particular day because we did it all in one go, it was a bit confusing. I think I didn't fail, but I just I didn't do as well as I probably could have. In time, I probably would get better.

R: That makes sense. Okay and then for the third stage, when you were wearing the hand and doing tasks with it, you had it down at 90 out of 100. So very high performance.

010: I think that was because we eased into it. When I was picking the paper up you coached me a little bit.

R: Yeah, we had practise beforehand.

010: I mean a lot after that is because of the orientation of the hand. It's not an ideal hand, you've

got to manoeuvre it. But the more practise you get with it, the better you get at it.

R: The next one I'd like to talk about is frustration. On stage 1, you said it was very low, it was 5 out of 100. In stage 2 that went up to 30 out of 100. Then stage 3 was 30 out of 100 again. Do you remember what it was that contributed to feeling frustrated or not frustrated?

010: Frustration... I do still get frustrated now trying to do things, when I know I've got to do things or I'm trying to do things. With a lot of communicating with the hand and making the hand do things that I want it to do. It's all foreign equipment to me. I wanted to do better – when I'm trying to do something and it doesn't work, that's when I get frustrated. I get frustrated most days, but it's just because I'm expecting to do things, and it working. When it doesn't work that's where the frustration comes in. It's the same with the hand. Is that the about the communication between like my brain and the [electrodes]? It's the time thing: I'm trying to make it do something that I want you to do, but I'm waiting for the system catch up with what my brain's trying to do, and that's where the frustration comes in.

R: Okay. And throughout the study, though, your frustration was you when we asked you about it, you always said it was quite low. Do you have any idea why it was so low?

010: I think part of it is because I think part of me part of me knows that it still works and given the right sort of equipment, it will probably work better. So I'm not as frustrated as I could have been. Knowing that the stuff that you've made does actually work and then me getting it to work as it should do. I could have got more frustrated but I I'm not a frustration kind of person. I've got more frustrated that have lost my arm but I'm pragmatic. If there's something to be frustrated about, I will. But if there isn't, I don't. My wife will disagree – she said I've got more frustrated and more angry since I've lost my arm. I don't think I am. We'll agree to disagree.

R: Okay, out of interest – why would your wife say that you've got more frustrated since losing your arm?

010: [She'd say that] my frustration levels of gone up since I've lost my arm. I don't think they have. I get frustrated. I don't get frustrated with her. I get frustrated with myself when I'm on my own and I'm trying to do something. For instance, if I can't open a jar and I'll use one of my tools to try and open it and still can't open it. I think that's natural because but I've never [struggled to do] that before. I didn't [struggle] to do it before. I do get frustrated a lot more. I don't get angry, just frustration.

R: Okay, so when you can't do something that you could have done before – is that a frustrating feeling?

010: I could get overly frustrated about, like, putting on shoes. Nice shoes have laces, and I can't do

the laces, but I bought elasticated laces or slip on shoes now so that that's a frustration that I haven't got anymore. I could get frustrated, but I don't.

R: This independence?

010: I don't like to ask anybody for anything. I don't ask anybody for help. I just want to do everything myself. Knowing full well that it takes that much longer to do it. If I ask for help, obviously the help is there. But like, for instance, if I needed to go out before I got my car back and everything, and if I wanted to go into town, I'd rely on my wife to take in town, knowing that I could have asked other family to help. Or I could have asked my mate or anybody to help. I just wouldn't. I'd rather either walk, get the bus or rely on my wife. It's an independence thing. When you've always had your independence and it's taken away from you. I draw a line if there's something I cannot physically do, then I will ask. I'm a proud man. But if there's something I cannot do physically, then I'll ask. I'm not stupid, but I prefer to be able to do things myself. Like right now I'm retired, so if there's something I need to do, I'll take that much more time. I need [more time], but I'll get it done. It's just part and parcel of an amputation. I will get things done, because I'm determined to get them done. Like today, I've been chopping logs and I've used this [static prosthesis] for the first time because it's easier to sweep up. I [usually] do it one handed, and it tends to like wear this arm out at my shoulder. Doing it today with [the static prosthesis] – so much easier. I've got something to actually brace the brush against. I shall use it more, for cutting the hedges and stuff like that. I'll use it more. I do get frustrated but if I can find a way around something, I'll find a way around it. On the day that you came because all the equipment was new to me and stuff like that, I was a little frustrated. I wanted it to be better, but because the equipment was new to me and everything, it was mildly frustrating, but not overly so. The equipment's new to me. You're out in the field doing research, so things don't necessarily work. So this first the levels of frustration, depending on what happens. It would have been lovely for you to come and everything worked perfectly, but it didn't. It would have been lovely for me to put the arm on, put the [electrodes] on and get the feedback and everything to have worked perfectly but doesn't work that way. That's that's life.

R: Yeah. I'm going to move on to the [embodiment statements]. The first one I would like to ask you about is the statement that said "the prosthesis is my hand". Before we started, before you'd used it at all, you already said you somewhat agree. Then after you'd used it, and it stayed this way for the rest of the study, you said agree. I was wondering what it was that made it feel like it was your hand.

010: I think initially it's somewhat agree in that it felt part of my arm, but only to a small degree because I've never used it before. Having something there that I can actually manipulate, move.

The more that I operated it the more it felt like it actually it was or it could be my hand in the fullness of time, when technology gets better and money's more available. I can go to America now if I've got like 100 grand or 250 grand and I could get one fitted perfectly and it will work perfectly. But until then, it's just luck. That would feel like a proper arm. I mean I look at this [static prosthesis] now, it's practical – it doesn't look like me all. The more you get to used something, though. I'd like a hand and arm, just so that I can use like a pair of hands again like instead of one. I've noticed different things when we've been away on holiday and things like that. [Myself and my wife] think that people don't come up to us now because I'm obviously not wearing an arm. They don't come talking to us now or interact with us because I'm disabled, we get that feeling as if it's because I've got no arm. Whereas we went with another couple and people were talking to them a lot, weren't they? But they wouldn't interact with us. It's like because you've got no arm. People tend to like, stay away from me. As if I've got the plague or something. I [know a person], if he's wearing like a suit, something like that, he's got this [prosthetic] hand there that's just static. That's just sitting there. I'd rather not do that.

R: You mentioned when you were speaking a minute ago. Were comparing the one you're wearing at the moment, which is a static prosthesis with a... it's like a claw, but it's more like a clamp, right?

010: Yeah.

R: And you were saying that you've got this one, but it doesn't like look like a hand, and the one we used in the study looked more like a hand that you were you moving around? How does the look of it – it having four fingers and a thumb, how does that come into play with it feeling more or less like your hand?

010: Well, because it looked like a hand. The one that you brought down, that is like an active one: it will actually move. This [static prosthesis] doesn't move and it won't move, it just basically [clamps]. Whereas the one that you brought down actually [produced], you know, movement in each [finger].

R: Okay to follow up on that slightly. Let's say that I brought [the prosthesis] and it looked the same as that [static prosthesis] there, but you could move it. I'm trying to understand, I guess, how important is it to you to have, say, fingers and a thumb that move?

010: If I'm going to have a prosthetic hand, I'd like a proper prosthetic arm that actually does work. Whether they will work with my little finger and ring finger [I'm not sure]. [In those fingers] I feel a little movement, but it's very slow, but if I had [a prosthetic hand] with just the three fingers on but I could move them quite well, that'll be that'll be enough. I'll be happy with just three, but I think if there's the possibility of getting all four fingers and a thumb working. If

I'm going to have a hand, I'd want all of them to work. But whether they all would or not, I don't know.

R: What I'm trying to understand is, in your mind, the different factors that make up something being your hand. You've mentioned how important it is for it to be able to move. Is that to do with you being in control of it?

010: Well, I suppose so, yeah. Suppose it would feel a bit like normality, wouldn't it?

R: Or is it being able to see it move or is it being able to feel it move or something else?

010: I think, in part, it's all of them. My brain knows it can actually [control a prosthesis] now. I've always known that I could do it. I can physically [move the muscles]... It's a bit of everything really. If I'm going to have [a prosthesis] I want it all to work. If I can get it all to work then it feel more like my hand. This [static prosthesis] just feels like a tool. With the with the [tasks] that I want to do, for 3 1/2 years now, I've done without [a prosthesis] and I can do 85% to 90% of what I could do before. It takes a little bit more time. With this [static prosthesis], or the other [static prosthesis] for the push bike and [playing] pool, I know exactly what they're for. I don't tend to use them for anything else apart from the push bike and pool. I know this has only got a certain amount of light usability if you like. I'm quite happy with what it can do. But having a hand to be able to do 95% to 100% of what I could do before... In time it will come, but at the moment it's a long way off. Knowing that all the impulses are there to do movements like a normal hand. That's given me hope.

R: Okay, I'm going to ask you about the next statement. The next statement is "the prosthesis belongs to me". Before we started, you said strongly disagree. After the green bars, matching the position it went up slightly to disagree instead of strongly disagreed. Then, after the blindfold task that went up again slightly to somewhat disagree. After you'd worn it, it went up to agree. What made it feel more or less like it belonged to you.

010: I don't know really. With more use it could. In terms of belonging to me, I know it's only a research and development 'tool' if you like. It's never going to belong to me. But if it was developed more? It should [feel like it belongs to me]. I mean, part of it is just wanting a hand again. Wanting it to belong to me. When it's fully working and I can actually use it on a daily basis, then it will feel more like it belongs to me. I know that one's not going to belong to me because, it's not quite finished. You're developing it now, but in five or ten years' time, there are going to be leaps and bounds [of development]. Whether I'm going to be young enough to benefit from that, I don't know. It will come in time; you'll go to the shop and say "ohh I've I've lost my arm". Then you'll just put [a prosthesis] on and it will work. It's like anything in medicine goes in leaps and bounds, so in time I will get one, but whether I'll be too old for it, I

don't know. Then it will belong to me.

R: That makes sense. So in stage 3, the other part that I'd like to ask about is: when you wore it, was there anything about putting this prosthetic hand onto your arm that changed the way you felt about it.?

010: It's still early days. The equipment, the feedback actuators. They need more work because they are quite basic and quite bulky. But in years to come, you'll just slip it on and that'll be it or it'll be engineered into your arm.

R: Okay. The next one is "I feel as if I'm looking directly at my own hand rather than that of prosthesis". Now for this one, after stage 1 that went up very slightly to disagree. After stage 2, after the blindfold task, that went slightly up again to the somewhat disagree, then after you've worn it, it went up slightly to neutral. What would it be about a prosthetic hand that would make it feel more or less like it looked like you're looking directly at your own hand?

010: Familiarity with it, to be honest. Everything on that day was all new to me. The more you wear it, and the more you get used to it, and the more you can operate it the way you want to do. By the end of the day, it was good to know that I can actually use it and it worked.

R: I remember you saying at the time while you were filling out [the questionnaire], you said, "well, it's red, this isn't going to look like my own hand".

010: It's just appearance that is, that's just appearance. I mean, I'm never going to have one that's going to look like my own hand again. Without an arm, people are going to stare. With a prosthetic arm that's flesh coloured on people are going to stare. I would rather have something to stare at, that's why I've gone for the carbon fibre and aluminium [static prosthesis]. If I have the option, I'll have a Terminator one. I'm at the point of life now, where I just don't care. People can point at me, stare at me, laugh at me. I really don't care. Doesn't bother me one little bit. I've been out on my bike and the kids are coming out of school. On a sunny day you can see I've only got one arm, but it's like a different arm. I've never had any sort of like bad things happen and never had any sort of bad things said to me. Some people with a disability, like an amputated leg or amputated arm, they wouldn't go out because they feel so self-conscious about it. But I'm not going to live my life [like that] just because I've lost something.

R: Okay, I'm going to ask you about the next statement. This next one is "my body feels complete". At the beginning, when we asked, you said you strongly disagree. Then when we started using the prosthetic hand and for the rest of the study, you said you somewhat agree. I was wondering if you could shed some light on that a little bit about what makes your body feel complete.

010: At this particular moment in time, I know my body is not complete because I can look at [my arm], it's gone. I know it's never going to be complete again. Even with the best prosthetics

going, it's never going to be complete because I know that bit is not quite real. As long as it will do what I wanted to do, I'll be happy. I know it's never going to be complete, but I can't do anything about that. I'll get something like a prosthetic arm that actually does what I want it to do when I want it to do it. It's like this [static prosthesis], I've actually got a physically think about [donning] this one to do the job that I want to do. The rest of the time I don't bother wearing anything. I've actually got to physically think about the tasks I'm going to do. When it comes to the time when I don't have to think about that, I'll just get up in the morning, put it on and it work exactly like my arm. Then it'll be more a part of me.

R: This idea that it could do many tasks instead of just one task?

010: Ideally, in time, I will get one that will do everything I wanted to do. Whereas at the moment the ones I've got they do specific tasks. I've got to physically put it in a bag, take it with me, put it on when I get there. When I go out on my bike, I've got to physically put it on. When the day comes when I don't have to think about that. That'll be completely different altogether. They can keep supplying me with all the tools and terminations that will do the things that I wanted to do, that's all well and good. Until the time that I can actually get an arm that I don't have to think about. To be complete with a normal arm that will do everything, that's the goal. At the moment I'm just a man with one arm and some tools.

R: Interesting.

010: I'm used to the versatility that I had before because I was an engineer. I was using both hands everyday. When you lose one of them, it takes a bit of getting used to. Until I get that versatility back, which I don't think I ever will, as long as I can get to 80% of what I could do before. And if that 80% comes with a range of tools, that's fine. I'm never going to be like the man that I was. I'm not going to be complete again, but I accept it.

R: Thank you for that, it was very in depth. The next one I would like to ask about is "the prosthesis moves the way you want it to move". After the position matching task, you said neutral, then after the blindfold task it went up to somewhat agree. Then after you wore it and did tasks with it, it went up to agree. Do you remember how the prosthesis was moving and how it related to how you wanted it to move versus how it was actually moving?

010: I had to move my [phantom] hand in a certain way. Like if I moved my hand downwards, that rotates the [prosthesis]. It's a bit like I'm trying to make [the prosthesis] do one thing, but you've got to make your [phantom] do something different. That's a bit confusing for me, I was expecting to rotate my [phantom] hand. But like you said, because of all the nerves are close together, picking individual [actions] up [is challenging]. It takes a bit of getting used to.

R: Okay and the next one is "I am in control of the prosthesis". For every stage here you said you

agree. Do you remember much about feeling the sense of control over the prosthesis?

010: Initially, I didn't think it was going to work at all. But seeing it actually work gave me [a feeling] like watching [something that I can actually control. I felt happy that I could control it from the word go. I didn't feel it was there was a time when I wouldn't, when I couldn't control it. The longer it went on, the less control I'd got because I was physically getting tired. I hadn't used those muscles or anything like that for 3 1/2 years. And doing all that in one go [was tiring], but it was good. It was good to see at the end of the day, that I could control it to a degree.

R: I'm going to ask about the last statement now, which is "the movement of the prosthesis feels like an actual movement". So after the position matching task you said you agree. Then after the blindfold task, it went down slightly to somewhat agree, and it stayed there for the rest of the study. What about it made it feel more or less like an actual movement that you were making?

010: That's because I can actually physically see something moving. Right now I can do all the controls just by thinking about it. But actually being able to physically see with my eyes, that's what made it more believable, more real. I can still do it now, but that's just me thinking about it and imagining my arm there doing it. Being able to actually see [the prosthesis] do it, that's the bit that made it more real.

R: Did being able to see [the prosthesis] do that change how much, say, it felt like part of your body or part belonging to you?

010: Because I could think it and see [the prosthesis] do it. That made it feel more part of my body and more real. Instead of just thinking about it and thinking it's doing it, but seeing [the prosthesis] doing it, that made it all real.

R: Okay. We've gone through all of the statements I wanted to talk about specifically. Before we finish I'd like to ask you if there's anything you would like to talk about that we haven't covered already?

010: No, I don't think so. I enjoyed the day it was informative, and it does give me hope for the future. Knowing that the impulses are still there and I can still do most of what my hand could do. I enjoyed it. It was good.

Appendix B

Appendix for The Controlled Prosthesis

B.1 Tables

Task	Group	Age/years	Gender		Handedness	
			Male	Female	Right	Left
Flicking Task	Non-Humanoid	25.8 (4.7)	5	3	8	0
	Humanoid	26.6 (3.2)	5	3	7	1
	All	26.2 (3.9)	10	6	15	1
Screwing Task	Non-Humanoid	23.9 (2.2)	5	3	6	2
	Humanoid	25.1 (3.3)	5	3	7	1
	All	24.5 (2.8)	10	6	13	3
Stacking Task	Non-Humanoid	26.1 (2.7)	5	3	6	2
	Humanoid	26.4 (2.5)	5	3	8	0
	All	26.3 (2.5)	10	6	14	2
Cutting Task	Non-Humanoid	26.1 (2.4)	5	3	6	2
	Humanoid	26.0 (2.5)	5	3	7	1
	All	26.1 (2.4)	10	6	13	3

Table B.1: Characteristics of groups of participants without limb difference for each task. Age, gender, and handedness of groups of participants without limb difference. For age, standard deviation is shown in brackets.

ID	Age	Gender	Affected Side	ULD Level	Cause	Years Since	Dominant Hand	Own Prosthesis	Frequency of Use
1	43	Male	Both (Right)	Below Elbow	TI	10	Left	Body-Powered	Daily
2	46	Female	Right	Below Elbow ^a	TI (PS)	24 (6)	Left	Static	Infrequent

Table B.2: Table of participant characteristics of individual participants with limb difference. For bilateral upper limb differences the side tested is shown in brackets, and details for the tested side are shown. Causes listed: traumatic injury (TI), planned surgery (PS). ^aParticipant 2 acquired their ULD via planned surgery after a prior traumatic injury, and received targeted muscle reinnervation; the muscles of the upper arm were used.

Item	Question
1	“The prosthesis is my hand”
2	“The prosthesis belongs to me”
3	“The prosthesis is part of my body”
4	“The prosthesis resembles my body in terms of skin tone, freckles, or other visual features”
5	“I feel as if I am looking directly at my own hand, rather than at a prosthesis”
6	“My body feels complete”
7	“The prosthesis is in the location where I would expect my hand to be”
8	“The posture of the prosthesis corresponds to that of a real hand”
9	“The prosthesis moves the way I want it to move”
10	“I am in control of the prosthesis”
11	“The movement of the prosthesis feels like an actual movement”

Table B.3: Prosthesis Embodiment Questionnaire for Upper Limb Prostheses. The questionnaire used to assess prosthesis embodiment for upper limb prostheses. Each question is answered using a 7-point Likert scale.

B.2 Figures

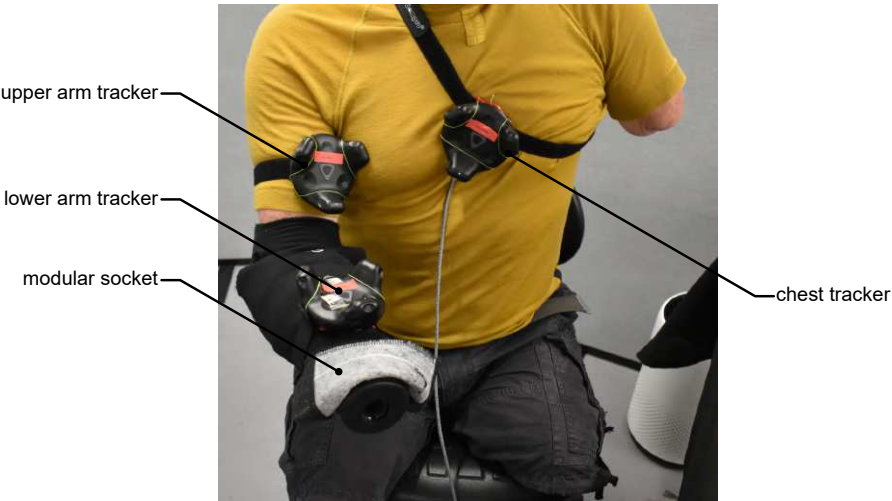


Figure B.1: Worn setup used by participants. Chest, upper arm, and lower arm trackers and socket worn by participant 1 with upper limb difference.

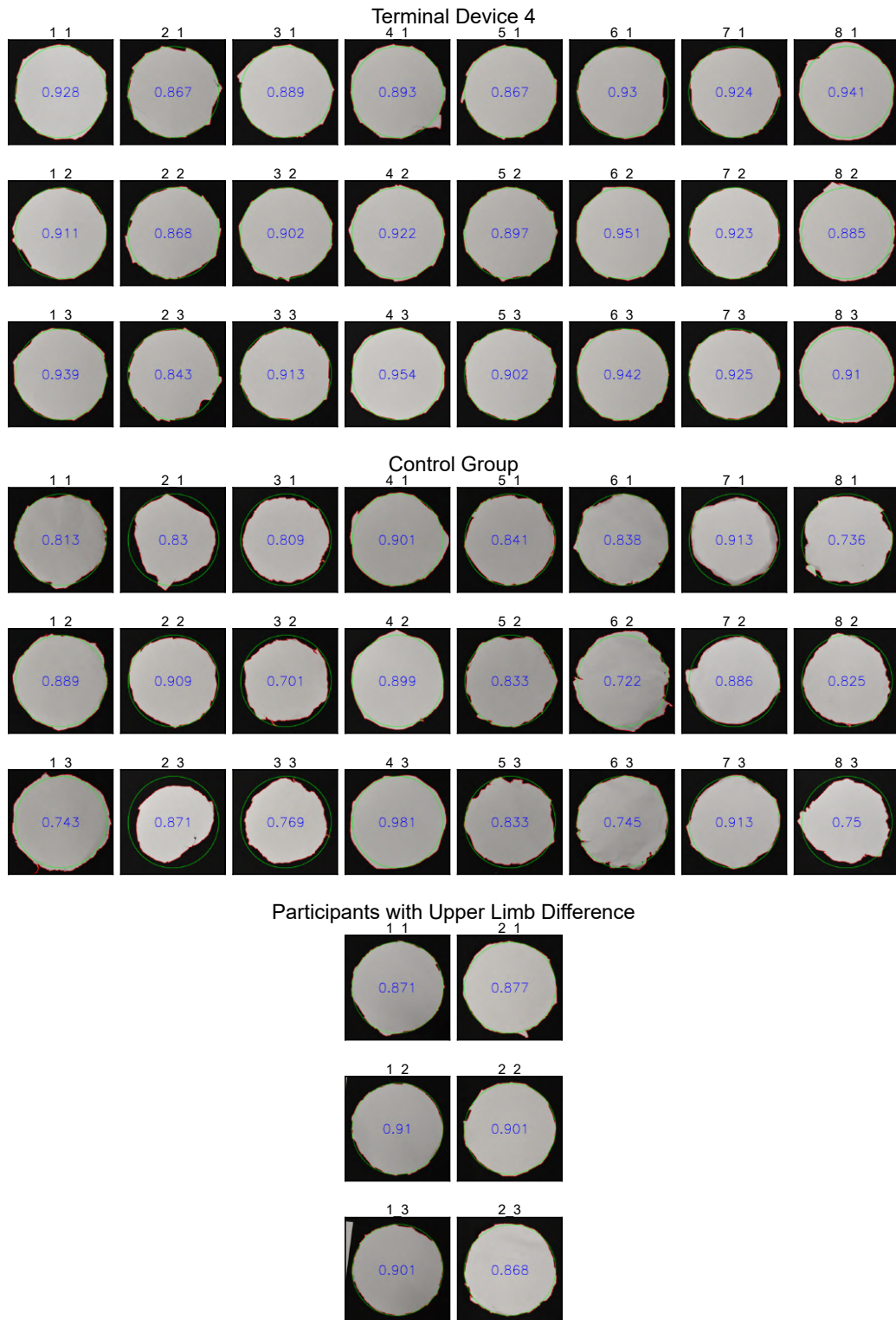


Figure B.2: Circles cut by participants for the circle cutting task to test Terminal Device 4. Top: Circles cut by participants using Terminal Device 4. Bottom: Circles cut by participants using the anthropomorphic hand. Each circle is annotated with its relative circularity (blue numeric value in the centre of each circle), target shape (green outline), detected contour (red outline), and participant/attempt (P_A , above each circle).

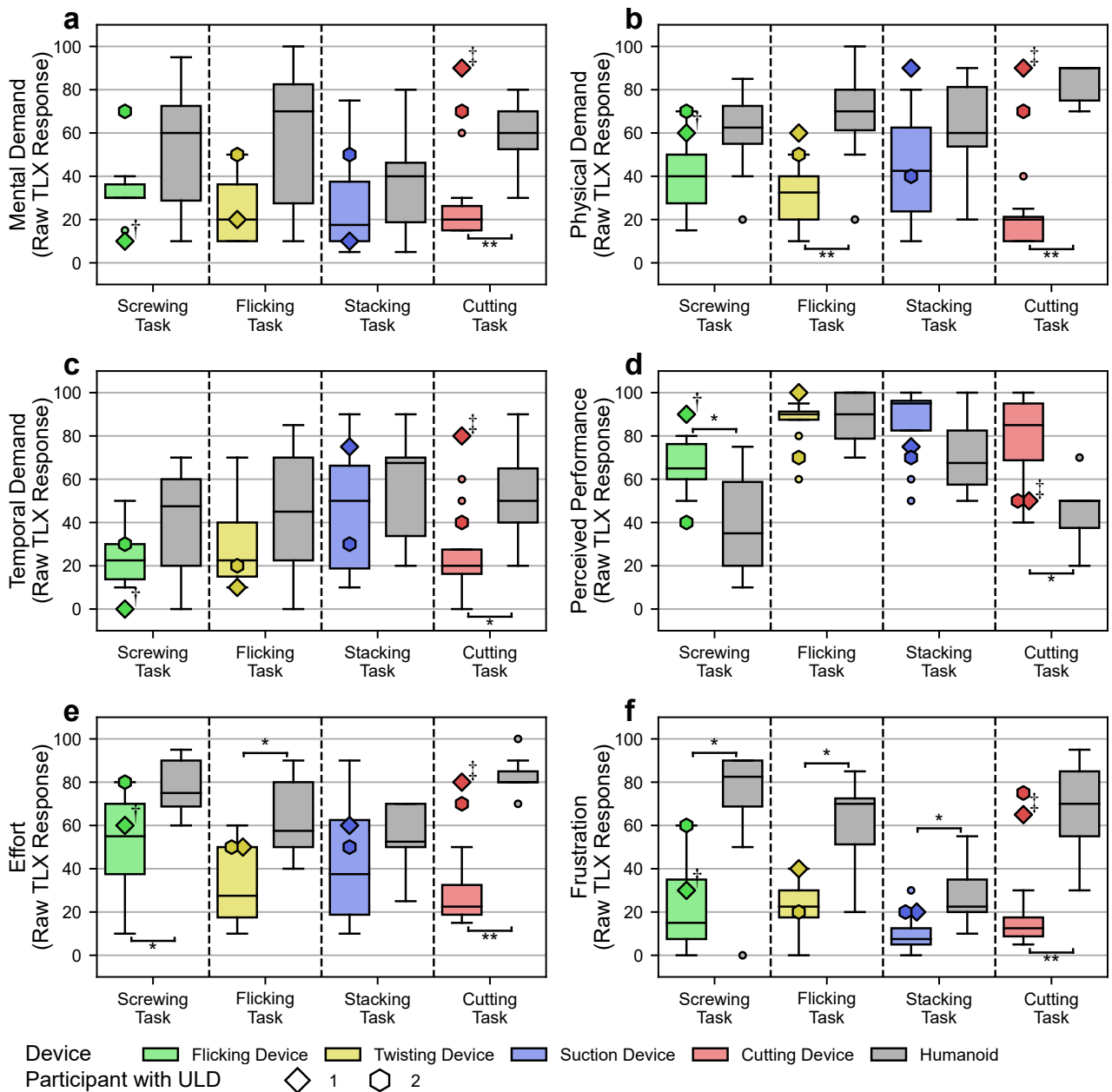


Figure B.3: Responses of participants to all questions of the NASA Task Load Index questionnaire. Raw TLX responses to **a** mental demand, **b** physical demand, **c** temporal demand, **d** perceived performance, **e** effort, and **f** frustration for each device on their corresponding task. All plots show results of paired two-tailed Mann-Whitney U tests: * $p < 0.05$, ** $p < 0.01$. † The screwing task was completed by participant 1 with the assistance of a carer, as it was a bimanual task. ‡ The cutting task is a bimanual task; participant 1 used their left residual limb (above elbow) to hold and manoeuvre the paper that was cut.