Original Paper

Game-Based Rehabilitation for Myoelectric Prosthesis Control

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Abstract

Background: A high number of upper extremity myoelectric prosthesis users abandon their devices due to difficulties in prosthesis control and lack of motivation to train in absence of a physiotherapist. Virtual training systems, in the form of video games, provide patients with an entertaining and intuitive method for improved muscle coordination and overall better control. Complementary to the established rehabilitation protocols, it is highly beneficial for this virtual training process to start even before receiving the final prosthesis and to be continued at home for as long as needed.
Objectives: The aim of this study is to evaluate a) the short term effects on controllability of a commercially available EMG system after a simple video game based rehabilitation protocol and b) different input methods, control mechanisms and games.
Methods: Eleven able-bodied participants, with no prior experience in EMG control took part in this study. They were asked to perform a surface EMG test evaluating their provisional maximum muscle contraction, fine accuracy and isolation of electrode activation, and endurance control over at least 300s. These assessments were carried out a) in a Pre Gaming session before interacting with three EMG controlled computer games, b) in a Post Gaming session after playing the games and c) in a Follow Up session two days after the gaming protocol to evaluate short term retention rate. After each game, participants were given a user evaluation survey for the assessment of the games and their input mechanisms. They also received a questionnaire regarding their intrinsic motivation (IMI) at the end of the last game.

Results: Results show a significant improvement in fine accuracy electrode activation ($p<0.01$), electrode separation ($p=0.02$) and endurance control ($p<0.01$) from Pre Gaming EMG assessments to the Follow Up measurement. The deviation around the EMG goal value diminished and the opposing electrode was activated less. Participants had most fun playing the games when collecting items and facing a challenging gameplay
Conclusion: Most upper limb amputees use a 2-channel myoelectric prosthesis control. This study has shown that this control can be effectively trained by employing a video game based rehabilitation protocol.

Keywords: upper limb prosthesis control; upper extremity amputees; gaming; serious games; neuromuscular rehabilitation; intrinsic motivation; EMG control

Introduction

The initial control of a myoelectric prosthesis can be a frustrating experience especially after the already traumatic event of losing a limb. Due to the non-intuitive interface, which handles a complex mechatronic system, the cognitive demand for controlling the prosthesis is high and further delays the actual use of the device in everyday life [1] [2]. At least 50% of upper extremity amputees report problems with the prosthesis control and functionality [3] [4], which can be attributed to the need of receiving more training in handling the prosthesis [5] [6]. By providing more training opportunities, the user can fully benefit from the technical functions of the prosthesis.

In order to prepare the residual muscles as well as induce the specific brain plasticity, having an access to a prosthesis itself is not necessarily needed. Regaining muscle strength and coordination is a cognitively exhausting and repetitive process during which the proper execution of movements is re-established using surface electromyographic (EMG) feedback [2] [7] [8]. Through physiotherapy patients are presented with a variety of tasks promoting the development of coping strategies for dealing with the activities of daily living and as such introducing the embodiment of the prosthetic system itself. To effectively control their prosthesis, patients need to learn how to properly contract their muscles. Especially the strength of activation and isolation of a single muscle are important parameters [1] [9] [10].

Even though the standard rehabilitation program offers direct functional benefits, its main shortcoming is the lack of motivation for patients to pursue it without the involvement of a therapist throughout the lengthy process. To add to the loss of functionality, patients may suffer from post-traumatic depression, further decreasing motivation for rehabilitation [11]. Transferring traditional EMG rehabilitation protocols to a virtual setting and incorporating video games into the training process can potentially increase the patient's engagement and perseverance [12]. It additionally provides medical professionals with quantitative data of the one's performance.

Many studies report that the progress achieved during rehabilitation based on a playful concept is faster and superior to conservative physiotherapeutic exercises [9] [13] [14] [15]. These rehabilitation games are especially popular in older adults [16] and when treating patients affected by stroke [17] [18] and Parkinson's disease [19] [20]. Various research groups have addressed adding virtual games to an otherwise rather dull routine in the area of upper limb amputee rehabilitation. There is, however, a difference between virtual or augmented reality environments [9] [21] and using commercially available video games during therapeutic interventions. The latter provides a higher accessibility and allows patients to easily set up the

games at home. This way, games can be chosen that are proven to motivate the players, also over a longer period of time [15]. An example of such commercially available video games that have been interfaced using EMG signals is “Guitar Hero” [14]. This game based on rhythm and speed requires a fast reaction from the player and also an immediate transmission of the processed EMG signals to the gaming system. Similar to this, a rehabilitation concept of stroke patients uses modified version of the WiiMote control is used for rehab purposes of upper limb amputees in which EMG signals are matched to the keys of the WiiMote [22]. However, controls are only limited to two motions. Other groups chose a game similar to the arcade classic “Pong” during which the muscle activity is mapped into a paddle motion that is used to hit a ball into the opponent’s court [23]. Although those approaches can be motivating, the necessary actions are not very intuitive and are hardly transferable to the handling of a prosthesis [24].

This study presents an interface between a computer and a commercially available surface EMG electrode system (Ottobock Healthcare GmbH, 13E200), which is commonly used for controlling prostheses, to evaluate the short term effects on controllability after a video game based rehabilitation protocol.

Here, compared to previous studies, participants are prompted to not only conduct repetitive agonist and antagonist muscle activation, but also to train and exert sustained contractions over a short period of time, perform precisely timed contractions and elicit simultaneous contraction of both muscles or muscle groups - similarly to how patients would control a real prosthesis in order to interact with their environment.

Methods

Eleven able-bodied participants, which had no prior experience in EMG control, took part in appraising the benefit of the video game based training. The evaluated categories of the EMG controllability assessments consisted of a provisional maximum voluntary muscle contraction for calibration, precision control, electrode separation and endurance control by retracing a sine curve with the EMG signal. These assessments are further explained in detail in the EMG Assessments subsection. Three video games and their respective control variations were evaluated for their motivational factors and feasibility. Two questionnaires were given to evaluate 1) the video games and the input method, 2) the intrinsic motivation. This study was approved by the ethics committee at the Medical University of Vienna under the number 1301/2015 and all participants of the study have read and signed the consent form before taking the part.

A. Participants

Eleven naïve, able-bodied participants without any known neurological or muscular impairments participated in the study. All participants had normal or corrected to normal vision and were instructed and accompanied by the examiner throughout the whole study.

B. Experimental Protocol

Each participant was seated comfortably in front of a computer. Two active surface EMG electrodes (Ottobock Healthcare GmbH 13E200) were positioned on top of the prominent antagonistic muscles for wrist movement of the forearm on the non-dominant side. This was done in order to match the handedness of the amputees, which is always transferred on the intact limb regardless of the pre-impairment state. Amplification and electrode placement

remained the same throughout the sessions. Each electrode delivered RMS at the 100Hz rate of the recorded EMG signal following the embedded filtering and rectification.

Participants were invited two times and had three test sessions in total: One Pre Gaming and Post Gaming measurement, both conducted on the same day, and a Follow Up measurement to evaluate short term retention rate two days later.

Initially, participants were instructed to perform three basic EMG assessments - the provisional maximum voluntary contraction level, accuracy of electrode control and muscle endurance. After a short break, participants were presented with three computer games in randomized order. After each EMG controlled game, they were asked to complete a short user evaluation survey considering the gaming experience. After the third and final game, a modified questionnaire aiming at intrinsic motivation (IMI) was completed.

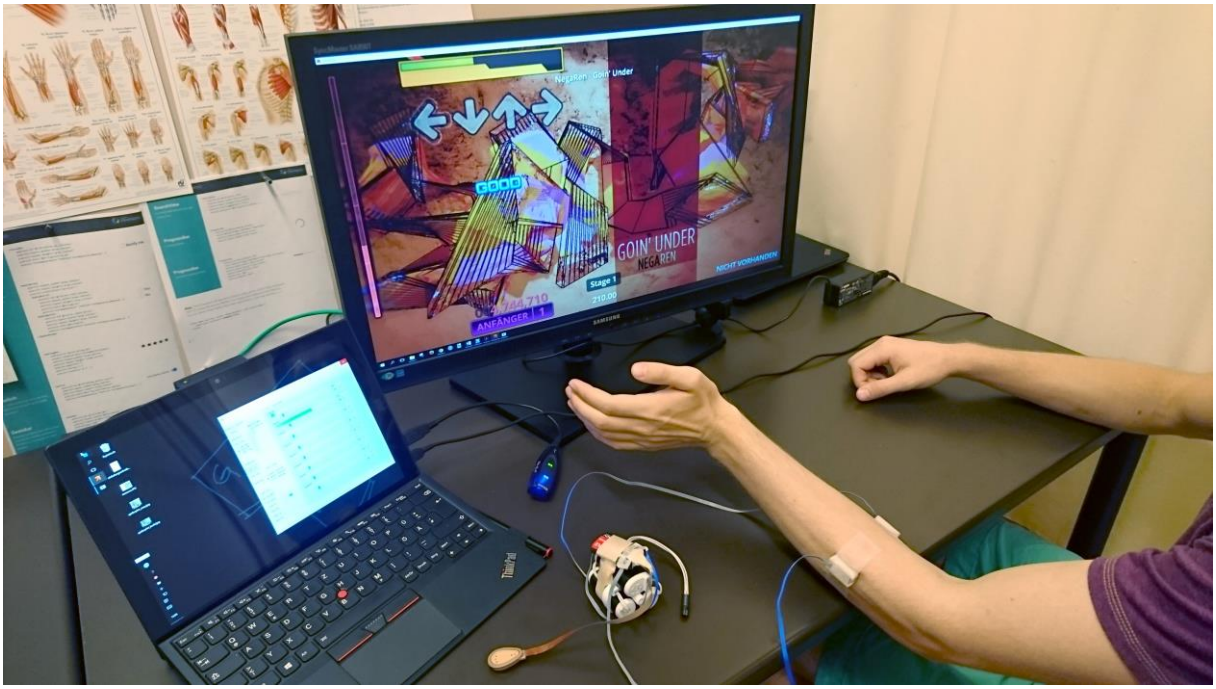


Figure 1 The experimental set-up. The participant sits in front of two computer screens. One screen displays the acquired EMG data per electrode channel, the other screen shows the game the participant is currently playing. The battery powered sensors used to control the games are placed on the non-dominant arm targeting the flexor and extensor muscles of the wrist. The EMG transmission is carried out wirelessly via a Bluetooth connection.

C. EMG Assessments

In order to investigate the changes in the overall controllability, three basic assessments evaluating approximate strength, muscle precision control and coordination, as well as muscle endurance were performed. Outcome measures considered are fluctuations of RMS EMG signals over expected EMG signals.

Maximum Voluntary Contraction Test

This test is used as a calibration of the voltage detected by the electrodes. It assesses the approximate maximum voluntary contraction (MVC) force averaged over 3 trials for each of the two electrode channels. Participants were asked to maximally contract one muscle and to hold this contraction for 1.3 seconds. Out of those, the last second was taken for calculating the activation baseline.

Assessment of Precision Control

The assessment of precision control test evaluates the participant's fine EMG control accuracy. The range of this test is adapted based on the outcome of the MVC test. Within the range of 10-90% MVC, the participant had to perform three trials per electrode of reaching a mark using the EMG signal. For each electrode, the participant is asked to reach 30 randomly preselected activation levels, and sustain them for 300ms each. The required level of activation is indicated by a triangular mark on the EMG bar (see Figure 2a). A total of 30 marks, 3 trials consisting of 10 levels, were performed for each electrode. The percentile deviation from the mark was taken as outcome measure. Randomization of the goal activation marks took place once before the beginning of the study and was kept constant between all participants.

Assessment of Separation

This test is a subpart of the Assessment of Precision Control and determined whether participants are able to separately control one muscle or if the opposing electrode is activated (co-contraction) during the tasks of the Precision Control assessment. Depending on the MVC, a threshold was set which corresponds to the point of EMG activation at which an electrode is considered active (see Figure 2b). It was set at 15% MVC. This concept of reaching a certain threshold for activating the electrode corresponds to the actual execution of prosthetic movements [1] [25]. The outcome measure is the binary activation of the opposing electrode and the overall percentage of activation of the opposing electrode per participant.

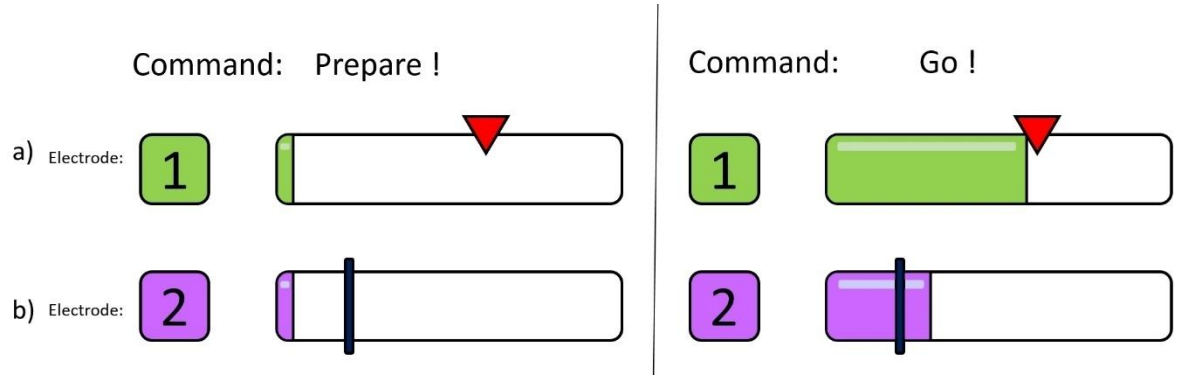


Figure 2 This shows the Assessment Interface for precision control and separation of electrode activation. Commonly both electrodes show some negligible offset activation due to the common noise during the idle state of the forearm muscles. In the depicted scenario, Electrode 1 is used to assess the precision control while electrode 2 indicates either a separate activation of both electrodes or a co-contraction. a) The red triangle indicates the goal activation level which participants have to reach with their EMG signals. After a preparatory countdown of 3s, participants have 1.3s to reach the marked goal activation. b) The black bar marks the threshold at which the electrode is considered active. If the EMG signal passed this bar, electrode separation failed and co-contraction is detected.

Assessment of Endurance Control

This test assessed muscle coordination and muscle fatigue while the participants use their EMG signals to closely follow a sine curve (1/4Hz) on the screen until they feel fatigued. The estimated force needed to reach the peaks of the sine curve corresponds to 60% MVC. A positive value corresponds to activation of the first electrode, while a negative value corresponds to the second. Electrode activation needed to be separate to reach the peaks of

the sine curve. The minimum time to be reached in this test was 15 minutes. Outcome measure was the EMG signal deviation from the desired sine curve given as correlation r^2 [26].

D. Games

Three different open-source games were used in this study: a racing game, a dexterity game and a rhythm based game. Each game features its respective control method (see Figure 3). The general input mechanism was to substitute keyboard events with EMG activation. Since participants control two electrodes, there are two concurrent keys possible at a time. Those motions represent one degree of freedom (DoF). However, to allow for more than just one DoF steering, participants can perform a co-contraction, a quick simultaneous activation of both opposing muscles, and switch to a second DoF. For games that do not offer the option of co-contraction to switch through keys, the dominant limb supports the control through direct keyboard input.

Racing Game

In the 3D racing game *Super Tux Kart* [27] the player races against the clock and computer controlled adversaries. The participant controls left and right turns solely with EMG signals, whereas accelerating and braking is controlled using keyboard input with their dominant hand. Required EMG activations are quick contractions and sustained contractions.

Dexterity Game

In the dexterity game *Pospos* [28] the player has to maneuver through a 2D labyrinth and collect items. This game is controlled entirely through the participant's EMG signals. Switching between the DoFs is done by co-contraction, which corresponds to controlling the horizontal and vertical axis of the player. Required EMG activations are quick contractions, sustained contractions and co-contraction to switch between DoFs.

Rhythm Game

In the rhythm based game *Step Mania 5* [29] participants are prompted to activate 2 different arrow shaped buttons using their EMG signal. The arrows have to be quickly pressed or held in time matching the rhythm of the note patterns that scroll across the screen. Required EMG activations are quick contractions, sustained contraction over a certain time period and co-contraction to simultaneously activate two buttons.

Game	Input Method	Player Control	Muscle Contractions
Racing Game (*SuperTuxKart*) 	EMG	Turn left, right	Quick contraction, prolonged contraction
	Non-EMG hand	accelerating, braking	---
Rhythm Game (*Step Mania 5*) 	EMG	Activate arrows left, right	Quick contraction, prolonged contraction
	Co-contraction	Activate both arrows simultaneously	Simultaneous contraction of flexor + extensor
Dexterity Game (*Pospos*) 	EMG	Move left, right, up, down	Quick contraction, prolonged contraction
	Co-contraction	Switch control axis between left/right and up/down	Simultaneous contraction of flexor + extensor

Figure 3 An overview of the 3 games played by the participants with their respective input methods, and the muscle contraction types needed to drive the game.

E. Questionnaires

Participants were given two questionnaires to fill in: a modified intrinsic motivation questionnaire and a user evaluation survey about the EMG assessment, played games and control methods.

Modified Intrinsic Motivation Inventory Questionnaire (IMI)

A modified 28-item version of the Intrinsic Motivation Inventory [30] [31] [32] consisting of five subscales was used to evaluate the experience with the played video games. The five subscales form scores for enjoyment, perceived competence, perceived choice, felt pressure and immersion. Additional 6 questions were added for the last subsection to evaluate immersion into the games. The questionnaire is adapted to the study by changing the words "working" and "doing" to "playing". It includes statements such as "I found the games very interesting" and "I felt tense while playing". The statements are rated on a 7-point Likert rating scale ranging from 1 ("no, not at all") to 7 ("yes, definitely").

User Evaluation Survey

The user evaluation survey consisted of 1) rating the played games, 2) rating the input and player control methods (see Figure 3), 3) rating the EMG assessment and 4) identifying

engaging elements within each game. This short survey about gaming experience was presented after every game and included questions about the gameplay, fun factor, motivation as well as input and control method.

F. Statistical Analysis

All analyses were conducted using IBM SPSS 20 and Matlab 2013b. Non-parametric tests were performed on data not meeting the requirement for normal distribution. The normal distribution was assessed via graphical interpretation showing normal Q-Q plots, and with Shapiro-Wilk test for normality as a numerical assessment. Significance was set at $\alpha=0.05$.

Maximum Voluntary Contraction

This test was used to relatively set the maximum contraction limit for the following EMG tests. It is given as average of the RMS electrode activation. MVC as measured 3 times, before playing the games, directly after and before the Follow Up measurement.

Assessment of Precision Control

The outcome measure for this test was the percent deviation from the 30 goal points per electrode channel. The deviation from the goal was calculated in absolute values and set in relation to the achieved MVC to derive a percent value of deviation for each goal point. All 30 data points are treated as if they would have been done consecutively. The goal points were divided into 3 equidistant intensity sections ranging from 10% MVC to 90% MVC. The Shapiro-Wilk test confirmed a normal distribution with $p<0.001$. The mean and standard deviation were compared for significance for the activation levels (low, middle, high) and for measurement sessions (Pre Gaming, Post Gaming, Follow Up) with a Bonferroni corrected paired samples t-test.

Assessment of Separation

Threshold crossings were given in percent for each of the 3 goal activation levels over the three measurement sessions. The 3 equidistant intensity levels range from 10-90%. Improvement was tested for significance with a related samples Wilcoxon signed rank test.

Assessment of Endurance Control

The conformity of retracing the sine curve as a correlation r^2 was computed for defined time windows consisting of 30s. The highest r^2 value was taken out of at least a 200s period. A related samples Wilcoxon signed rank test ($\alpha=0.05$) examined the Pre Gaming measurement correlation with the Follow Up measurement correlation.

Intrinsic Motivation Inventory Questionnaire

Participants had to rank the 28 statements from 1 to 7, where 1 represents “I do not agree” and 7 represents “I agree”. The statements belong to one of 5 categories and the ranking is averaged. An independent samples Mann Whitney U test was performed to describe the data. All categories except “pressure” have a high desirable rank.

User Evaluation Survey

This survey consisted of ranked statements on a 5-point scale and multiple choice questions regarding game experience and preferences that were evaluated through a frequency analysis.

Results

A. Controllability

Maximum Voluntary Contraction

The MVC was used only as a calibration for the electrode channel voltage. However, it could be observed that the RMS values for the maximum voluntary contraction test directly after the games, show an increase instead of the expected decrease. Moreover, the same can be observed for the Follow Up session.

Assessment of Precision Control

Results show a significant improvement in fine accuracy and electrode coordination from the Pre Gaming measurement to the Follow Up session ($p=0.001$). The deviation around the goal value diminished and overall distribution became more homogeneous (see Figure 4). In all 3 measurement sessions, low goal intensity was significantly easier to reach than high goal intensity ($p=0.002$).

Assessment of Separation

The opposing electrode was significantly less activated during low electrode activation tasks compared to high activation tasks in the Pre Gaming session ($p=0.02$) and the Follow Up session ($p=0.04$) (see Figure 5). A significant increase in performance can be observed from the first to the last measurement session for low ($p=0.04$) and medium ($p=0.02$) activation levels, however, not for high intensity activation (see Figure 5). Generally, there is a significant improvement in electrode separation considering the first measurement session and the last ($p=0.02$).

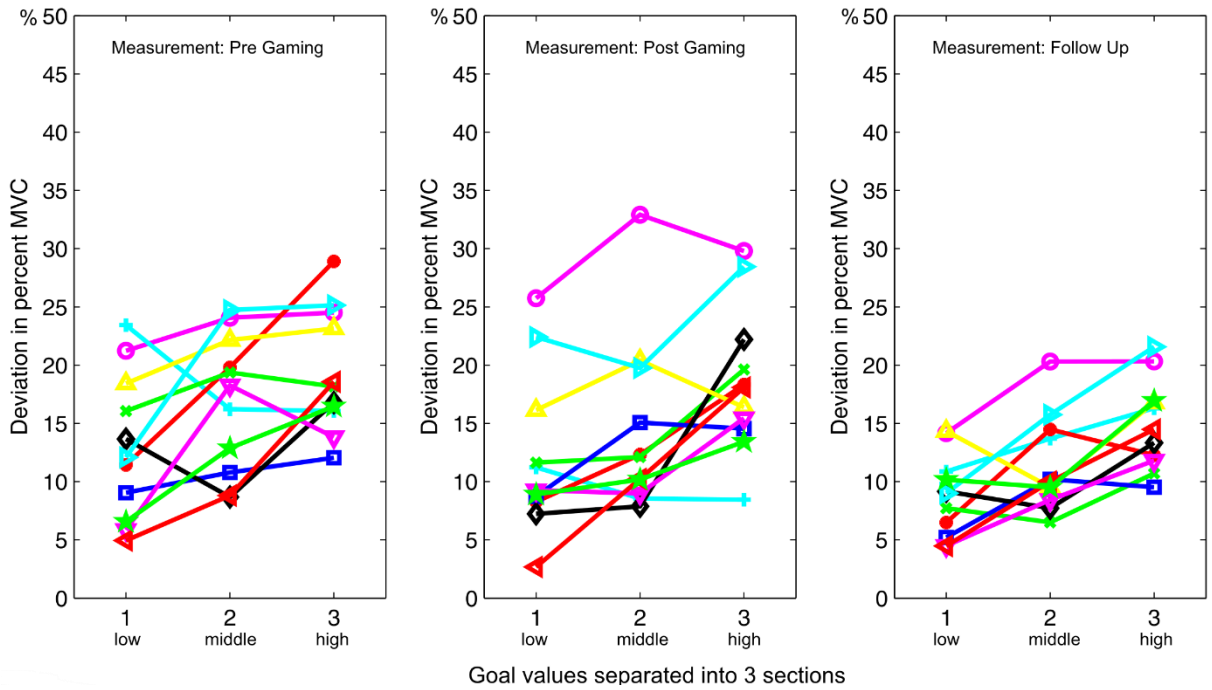


Figure 4. Each line represents results for each individual participant. Deviation values from both electrodes were combined. The development of percentile deviation of the electrode activation from the goal value (separated into low, middle and high goal values) through 3 measurement sessions (Pre Gaming - left, Post Gaming - center and Follow Up - right) is depicted here. Percentile deviation from the goal value is high and heterogeneous in the first two measurements, but significantly lower and more homogeneous in the Follow Up measurement (p<0.01). It was also significantly harder to reach a high goal value than a low goal value (p<0.01) during all 3 measurement sessions.

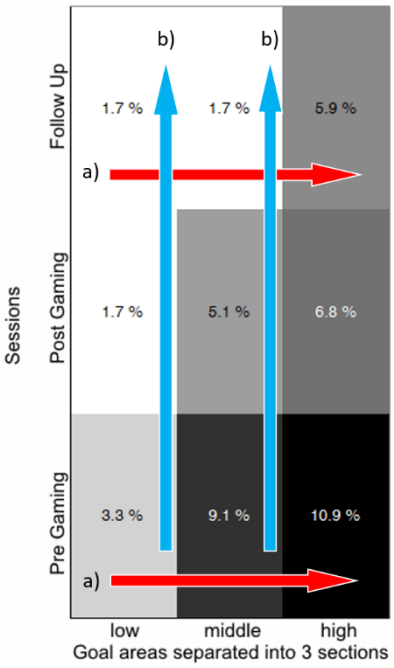


Figure 5. This figure shows the opposing electrode activations over 3 measurement sessions (Pre Gaming, Post Gaming and Follow Up) and 3 goal areas, the participants had to reach with their EMG signal (low, middle and high goal activation area). a) Significantly better performance can be observed in low goal activation compared to high goal activation for the Pre Gaming and Follow Up measurement (p = 0.02 and p = 0.04), however, not for the middle goal activation area (p = 0.06). b) The opposing electrode activation decreased from the Pre Gaming to the Follow Up measurement for all goal activation areas; significantly for low (p = 0.04) and middle (p = 0.02) goal activation.

Assessment of Endurance Control

Participants showed an improvement in muscle endurance control (see Figure 6). This is true for all but one participant, whose EMG activation expresses an offset and is shifted by a half a period of the retraced sine curve. Nevertheless, the Related Samples Wilcoxon Signed Rank Test determined a significant difference ($p=0.004$) in r^2 performance between the Pre Gaming and Follow Up measurement session.

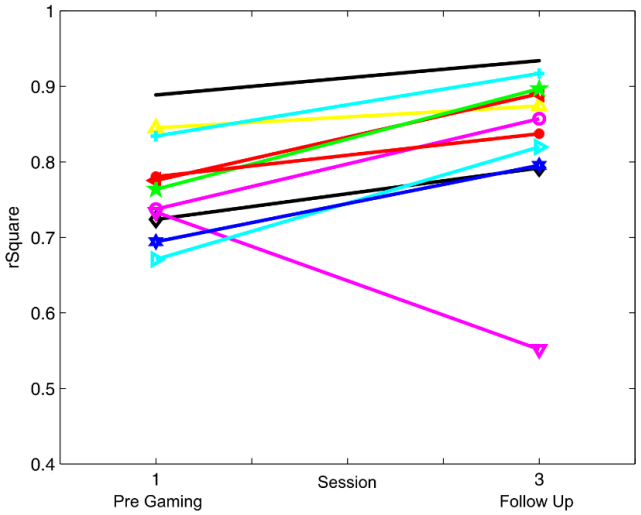


Figure 6. Here, the scores of the endurance assessment and comparison of the Pre Gaming r^2 value and the Follow Up value are shown. High r^2 corresponds to close EMG retracing of the given sine curve. Besides one clear outlier (pink curve with triangle mark), all participants improved significantly in EMG endurance control ($p<0.01$).

B. Questionnaires

Modified Intrinsic Motivation Inventory

The results obtained from the IMI questionnaire can be seen as mean and standard deviation of the five categories in Figure 7. Participants enjoyed playing the games and felt immersed. They perceived playing the games as their own choice and felt rather competent and at ease while doing so. Pressure was the only category in which a low rank was desirable.

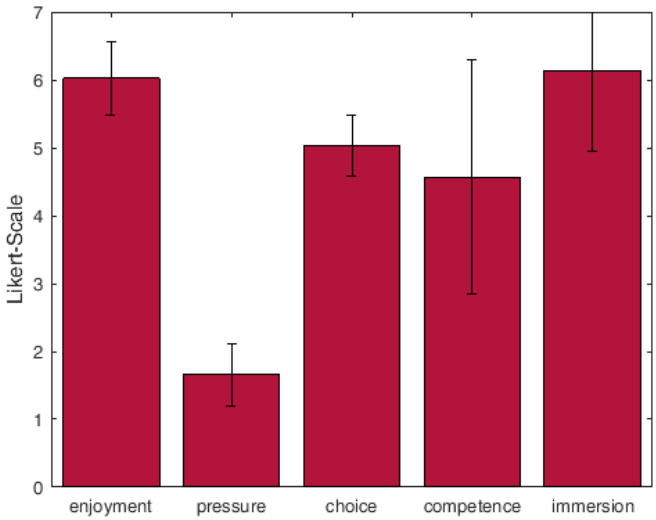


Figure 7: Means and STD for 5 subscales of the modified intrinsic motivation questionnaire on a scale from 1 (low) to 7 (high). Pressure is the only category to be expectedly perceived as low.

User Evaluation Survey

Participants were asked to answer five Questions (Q1 – Q5) for each game (see Figure 8). According to the user evaluation survey the most favorite game (derived from the score of Q1 and Q2) was the racing game Super Tux Cart followed by the rhythm game Step Mania 5. According to Q3 and Q4 participants preferred to control the games with EMG signals only and to perform different contraction lengths as well as co-contractions. In terms of motivation (Q5), the game for dexterity ranked far behind the racing and rhythm game which were almost equally well received.

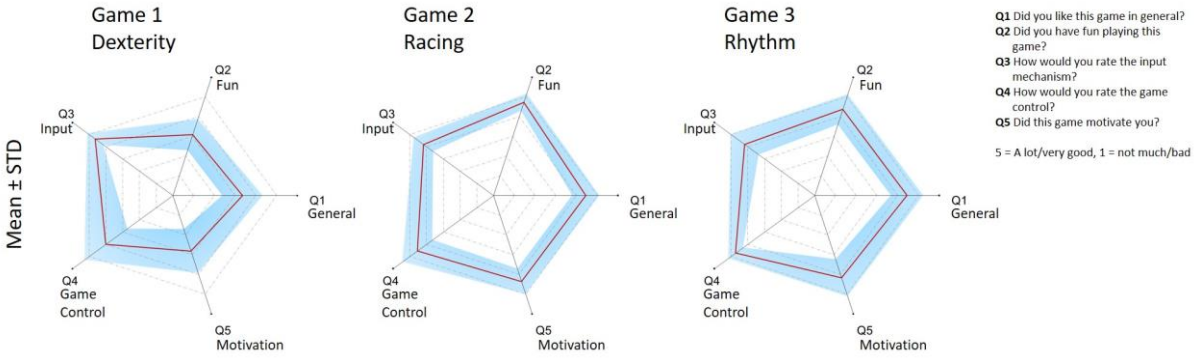


Figure 8: This figure shows the mean and STD rating of the 3 played games according to the survey participants had to fill in after each game.

Most important components to continue playing and enjoying a game were (listed according to importance) a) the EMG control method, b) the level of difficulty, c) dynamic movements and d) collecting items. Music, atmosphere and graphics rated last. Even though participants claimed to prefer 3D graphics, this does not reflect their rating of what they enjoyed most in the games. The most motivating aspects of games were a) the gameplay, b) to see one's own high score and c) to clear upgrades.

Additionally, participants had to rate the EMG assessments after each session. They were asked how important they thought of the importance of the EMG assessment increased until the Follow Up the EMG assessments were, and to rate the fun they had while doing them. As can be seen in Figure 9, rating measurement (however, not significantly), while the participants enjoyed them significantly less ($p=0.002$). Interestingly, there is a slight rise in rating the fun factor after the Follow Up session again.

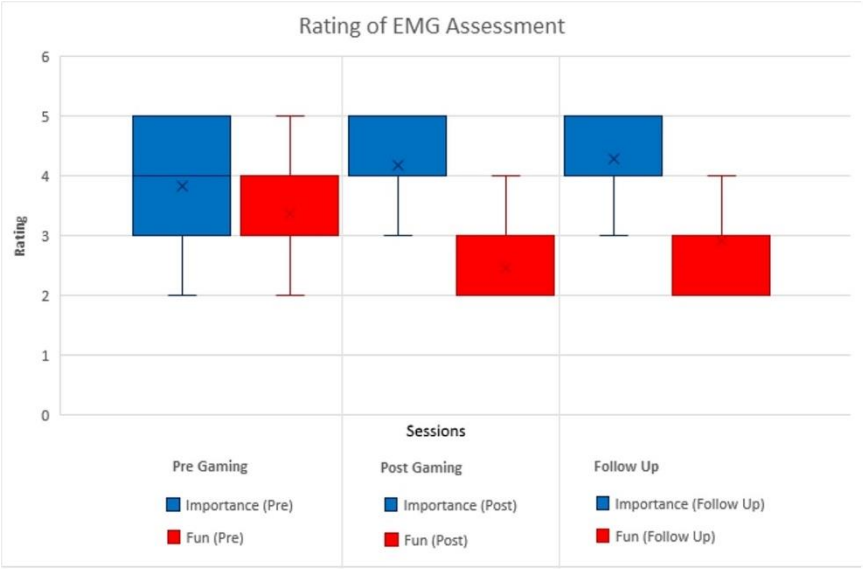


Figure 9 This figure shows the rating of the EMG assessment after each session. Rating could range from 5 (very important/fun) to 1 (very unimportant/boring). Rating of importance of the EMG assessment slightly increased, while the enjoyment significantly decreased ($p<0.01$).

Discussion

Results have shown improvement in fine accuracy electrode activation and electrode separation from Pre Gaming EMG assessments to the Follow Up measurement. Surprisingly, the MVC values, used as a baseline calibration, have also shown an increase instead of the expected decrease after playing the games. This could be either due to warmth or sweat that would influence the electrode resistance. Additionally, this is a solid indicator that the gaming session was not fatiguing for the participants. Their performance during the precision control assessment, however, declined after playing the games. If, based on previous investigations, we exclude the fatigue, it is reasonable to assume that participants started losing their concentration by the end of the session. In the Follow Up measurement, a clear improvement of performance can be observed which can be attributed to the restoration of the full focus combined with the obtained experience from the previous session.

Compared to previous studies [22] [23] [24] [33], participants not only conducted repetitive flexor and extensor muscle activation, but also to trained sustained contractions over varying periods of time, perform precisely timed contractions and execute simultaneous contractions of both muscle groups - similarly to how patients would control a real prosthesis.

The motivation aspects of training gamification are clear and probably the main advantage compared to the conventional techniques. Also, it is reasonable to assume that certain improvement of the EMG control could be observed by sole application of the listed EMG tests. However, the prolonged exposure to them would certainly lead to the loss of interest, which is sure to be maintained by the appealing context of a video game [15].

Limitations

The transferability of the obtained results to the amputee population might be questioned, since this study has been conducted strictly on healthy participants and this is yet to be further

explored. However, based on the outcomes reported in other myocontrol based studies [34] [35] it is reasonable to expect that the patient group will perform similarly.
Since this study was a short term intervention, it can be seen as a proof of concept. Further research will incorporate a long term evaluation of videogame-based interventions, as well as additional exploration of the advanced control mechanisms such as those based on machine learning approaches [36] [37] [38].

Conclusion

Most upper limb amputees use a 2-channel myoelectric prosthesis control. This study has shown that this control can be effectively trained by employing a video game based rehabilitation protocol. Participants significantly improved in electrode separation and fine muscle control. It could be shown that the enjoyment of the games was greater than that of the EMG assessments, which decreased over time. Additionally, engaging elements within each game could be identified. A subsequent study with an amputee population will show if the information gained from healthy participants can be transferred. The final outcome would be a robust system that patients can operate outside of a clinical environment.

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Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper. All authors have read and approved the final manuscript.

Abbreviations

EMG: Electromyography
IMI: Intrinsic Motivation Questionnaire
MVC: Maximum Voluntary Contraction
RMS: Root Mean Square

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