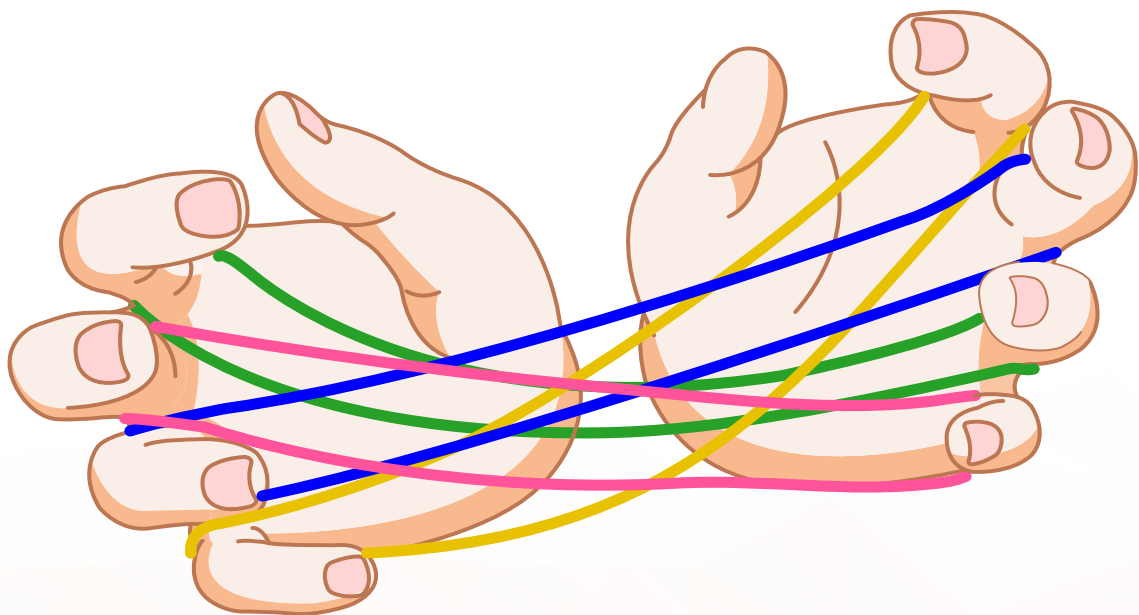


PHYSICALLY-COUPLED BIMANUAL COORDINATION IN CHILDREN

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ABSTRACT

This thesis explores physically-coupled bimanual coordination amongst *typically developing* (TD) children, as well as children with *unilateral spastic cerebral palsy* (USCP). Unlike TD children, who acquire bimanual skills through *activities of daily living* (ADLs), children with USCP exhibit sensorimotor impairments to half side of their body, that impede their ability to learn and adapt two-handed skills into ADLs. While bimanual training is increasingly being incorporated into rehabilitation, the evidence for its effectiveness in improving the functional capacity of children with USCP against standard care is modest at best. This thesis argues that there is a fundamental gap in the knowledge, thus impeding our understanding, of how bimanual skills develop and manifest under both TD and USCP conditions. Specifically, much of what we know about bimanual development in children comes from studies on *uncoupled* bimanual tasks, where the hands control two independent objects. Conversely, there has been a minimal effort to systematically quantify the behaviours underlying ubiquitous *physically-coupled* bimanual coordination, where the hands manipulate a common shared object.

Bimanual coordination of TD children and children with USCP was explored through four experiments that incorporated different forms of physical coupling (visual and haptic feedback), mechanics (modulating object stiffness), and congruence. This was achieved using instrumented objects, a robotic interface and novel metrics developed within this thesis that enable the elucidation of various synergies between the two hands to be quantified.

The first experiment explores visual feedback in bimanual coordination, by comparing the grip force control during unimanual and visually-coupled bimanual tasks. Both TD and USCP subjects exhibit deteriorated performance during bimanual manipulation relative to a unimanual equivalent, with the discrepancy significantly more pronounced in children with USCP.

The second experiment investigates how TD and USCP subjects maintain these bimanual grip force synergies even when the visuomotor perception related to one of the hands is perturbed. Both TD and USCP subjects show deteriorated performance following this perturbation, reflecting their ability to prepare grip forces through a feedforward strategy. However, for subjects with USCP, this process was deteriorated by their sensorimotor deficits.

The potential of natural haptic feedback was explored in the third experiment, with the investigation of how TD and USCP children lift a single object using both hands. No anticipatory impairment was observed amongst subjects with USCP. This is hypothesised to be due to the continuous exchange of haptic feedback between the two hands through manipulating a shared object — thus highlighting the potential of this feedback to allow subjects with USCP to compensate for their impaired sensory function and continue predicting the ongoing movement.

The final experiment investigates whether the observed benefits of haptic feedback are retained across different object mechanics. Specifically, the same virtual object is manipulated through a robotic interface allowing for subjects to experience different stiffness levels between the hands. It was found that, regardless of the stiffness, the benefits of haptic feedback retain, where healthy adults developed counterbalance strategy between force and positional feedback adjustment to maintain their bimanual coordination. However, this process deteriorates with softer object.

In summary, the findings from this thesis provide important implications for understanding the normal and impaired behaviour of bimanual action amongst TD children and children with USCP, as well as amongst healthy adults. Specific contributions of this thesis come from (1) development and application of a suite of instrumented objects and robotic interfaces to study the broader spectrum of physically-coupled bimanual tasks, (2) development of novel metrics, e.g. grip-load monotonicity to quantify and stratify normal and pathological behaviours in early childhood development, and (3) a deeper understanding of the interplay between haptic and visual feedback in shared object manipulation tasks. The results provide evidence that physical coupling may facilitate bimanual coordination, especially in the presence of haptic feedback. Therefore, this thesis proposes that true physical interaction during bimanual activities may provide a new opportunity for the rehabilitation of children with USCP.

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This thesis is dedicated to you

*"While we try to teach our children all about life,
our children teach us what life is all about."*

—ANGELA SCHWINDT

Dedicated to all children who were a part of this journey.
Thank you for teaching me what life is all about.

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LIST OF ABBREVIATIONS

ADLS	Activities of daily living
CIMT	Constrain-induced movement therapy
CP	Cerebral palsy
HABIT	Hand-arm bimanual intensive therapy
MACS	Manual ability classification system
SCPE	Surveillance of Cerebral Palsy in Europe
SPARC	Spectral arc length
TD	Typically developing
USCP	Unilateral spastic cerebral palsy

1 | INTRODUCTION

Most of us have marvelled at one time or another at how certain people make knitting seem so easy and effortless — carefully twisting and turning the two needles that are intertwined with the knitwear. Such skills are not innate; they can only be acquired with practice to coordinate the two hands with proper, concerted movements. Two-hand coordination, also known as *bimanual coordination*, can be defined as a task-specific and active assembling procedure where the two hands act cooperatively by virtue of mutual coupling (Sleimen-Malkoun *et al.*, 2011). Bimanual activities are ubiquitous to daily life, ranging from everyday household chores such as opening a screw-top jar, to hobbies such as playing the guitar or passing a basketball. Some of these activities, such as passing a basketball, demand the same action from each hand, while other activities require both hands to move in a different, yet complementary fashion to one another.

Bimanual actions can be carried out while handling one or multiple objects at the same time. Their control mechanisms can be classified into two categories:

UNCOUPLED CONTROL involves each hand moving independently to manipulate two separate objects. It can be *congruent*, for example, drawing two circles using both hands, or *incongruent*, where both hands are performing different but complementary actions at the same time, such as playing the piano.

PHYSICALLY-COUPLED CONTROL involves manipulating a single mutual object or multiple connected objects. Physically-coupled tasks encompass activities in which the limbs are mechanically connected, such as moulding a snowball, or virtually connected, such as controlling a game object with both hands. For a task to be considered physically-coupled, the force from one limb must affect the dynamics of the contralateral limb (Shirota *et al.*, 2016). The task can be congruent, where the two hands act in unison, such as lifting a big box, or incongruent, where one hand supports or stabilises an object while the other hand explores or manipulates it, such as opening a screw-top jar.

Bimanual movements involve a precise organisation of motor, perceptual and cognitive processes, constrained by both internal (i.e. biophysiological) and contextual (i.e. task) factors (Brakke *et al.*, 2007). One of the processes that plays a vital role in maintaining bimanual

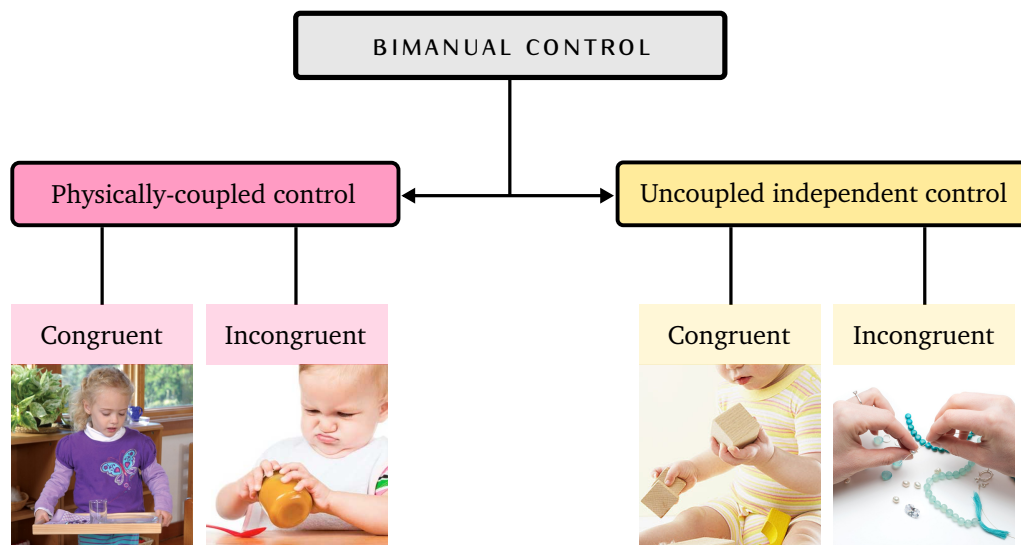


Figure 1.1 | Physically-coupled and uncoupled bimanual controls. Shown are the examples of physically-coupled tasks, which involve manipulating a shared object, and uncoupled tasks, which involve manipulating two or more object simultaneously.

coordination is *interhemispheric communication*. This process is mediated through the *corpus callosum*, the major neural pathway in the longitudinal fissure that connects the left and right hemispheres of the brain (Fagard *et al.*, 2001). The corpus callosum is responsible for the integration and transfer of sensory, motor and cognitive information between the two hemispheres; therefore an intact corpus callosum is necessary for motor planning, as well as for acquiring and developing new bimanual skills (Franz *et al.*, 2000).

The process of acquiring bimanual skills for children with *typical development* (TD) is achieved through activities of daily living (ADLs), such as learning to button their shirts or tying shoelaces. These children gradually learn to properly coordinate their hands while they continue to explore increasingly complex activities with both hands. However, for children with *unilateral spastic cerebral palsy* (USCP), this process may not be as straightforward — sensorimotor impairments to the half side of their body may impede their ability to learn and adapt bimanual actions like their TD counterparts.

Cerebral palsy (CP) is the most common non-progressive brain injury that affects 1 in every 400 live births worldwide (Disability Charity Scope UK, 2018). USCP is a subtype of CP that is caused by an injury to one side of the brain, before, during, or shortly after birth. As a result of this brain injury, children with USCP incur long-term impairments to the sensory, movement and posture of the contralateral side of their body (Rosenbaum *et al.*, 2007). Most children with CP and USCP encounter activity limitation and participation restriction, which increase their dependency and affect the quality of life of the children, as well as their families or caregivers. A significant part of their restricted participation is due to their bimanual impairment, which is more debilitating than their unilateral impairment (Gordon *et al.*, 2007). Therefore,

to address this problem, therapists began to incorporate bimanual-based interventions into rehabilitation for children with USCP, with hope to facilitate the functional use of the more impaired limb and to increase their range of ADLs.

Bimanual-based training is proven effective in encouraging adults with bimanual deficits, such as unilateral stroke patients, to (re)-incorporate the use of both hands into ADLs. Similarly, it is also efficacious at improving the functional capacity of children with USCP (Gordon *et al.*, 2007). However, Sakzewski *et al.* (2014) found that the benefits of this training against the standard care are modest at best. Such contradictory findings could be due to the lack of a comprehensive study that is geared towards understanding the development of bimanual skill covering a wide range of two-handed activities in TD and USCP children. Without this understanding, the current rehabilitation approaches may not be able to efficiently adapt the skills associated with the broader set of everyday bimanual actions.

Specifically, much of what we know about bimanual coordination come from the studies involving *uncoupled* bimanual tasks, such as two-object lifting, drawer opening, and bimanual reaching and grasping. These studies have not only dealt with healthy adults (Swinnen & Wenderoth, 2004; Carson, 2005) but also on neurologically impaired individuals such as stroke survivors (e.g. Sleimen-Malkoun *et al.*, 2011; Kantak *et al.*, 2017), children with USCP (e.g. Sugden & Utley, 1995a; Gordon *et al.*, 1999), and more recently, individuals with autism spectrum disorder (e.g. Piedimonte *et al.*, 2018). Only until recently researchers began to explore bimanual coordination during *physically-coupled* tasks. For instance, Contu *et al.* (2016) demonstrated that a physically-coupled task could provide intrinsic visual and haptic feedback, that cannot be acquired from a two-object task alone. The mechanisms underlying a physically-coupled bimanual task are particularly intriguing, as this task demands a distinctive control strategy from an uncoupled task, whereby both hands need to be coordinated in a complementary fashion to control the shared object. When performing activities with a physical connection between the two hands, both hands are engaged in a concerted spatial, temporal, visual and haptic interrelationship that characterises physically-coupled bimanual coordination.

Despite its capacity, the potentials of physically-coupled coordination for children, especially those affected with USCP, are yet to be explored. The benefits of performing a physically-coupled task for children with USCP can be grounded on two justifications: firstly, manipulating a single object with both hands physically connected – be it via virtual or mechanical connection – could redirect visual attention from two or more separate objects during uncoupled bimanual tasks, to a shared object. For children with USCP, who sometimes present with cognitive impairment, the shared visual attention, which ‘gives rise’ to the impression of controlling a single object, could potentially reduce cognitive load and facilitate faster and more accurate movement planning. Secondly, moving two mechanically connected hands al-

lows a continuous exchange of force information between the two hands. This information, which cannot be obtained via uncoupled tasks alone, may help individuals with sensory impairment like USCP to anticipate and adjust their ongoing movement.

The organisation of this introductory chapter is as follows: Section 1.1 outlines the motivation, research questions, and aim of this thesis. Background study begins with Section 1.2, which describes the mechanisms governing bimanual control, and reviews previous investigations into bimanual coordination. Section 1.3 reviews the typical development of unimanual and bimanual coordination amongst TD children from both behavioural and neurological perspectives. Next, Section 1.4 explains the aetiology of cerebral palsy (CP) and USCP, discusses the sensorimotor impairments secondary to USCP and reviews current rehabilitation practices for these children. Section 1.5 discusses the limitations of current clinical practices and proposes a model to classify bimanual actions based on the properties of the tasks. The proposed model reveals the lack of studies exploiting the potential of visual and haptic information yielded through physically-coupled tasks and is used to develop the framework of the thesis. Finally, Section 1.6 explains this framework and presents the research approach, thesis organisation and synopsis of each chapter.

1.1 THESIS MOTIVATION AND AIM

This thesis aims to *investigate the coordination of upper limbs during physically-coupled bimanual control* amongst TD children and children with USCP. This study is motivated by a growing body of research on healthy adults that have demonstrated how performing a task with two ‘physically-coupled’ hands could yield superior benefits over an uncoupled task, for example, by providing intrinsic visual and haptic feedback that cannot be acquired from a two-object task alone (Contu *et al.*, 2016). The distinctive coordination strategy of physically-coupled bimanual tasks from commonly studied uncoupled bimanual tasks raises the question of whether this type of task could yield superior functionality and benefits over controlling two objects separately? If so, what are the mechanisms that govern physically-coupled tasks, and how can they be adapted into the rehabilitation process for individuals with sensory and motor impairments like USCP? These are the questions underlying the studies in this thesis.

The insight gained from the studies in this thesis will enhance our understanding of bimanual coordination as a whole, and may eventually facilitate clinical advances. For example, in developing an optimal and well-rounded rehabilitation framework that encourages individuals with neurological impairments to incorporate the physical interaction of the two hands in their day-to-day activities.

1.2 MECHANISMS UNDERLYING BIMANUAL COORDINATION

Bimanual coordination involves an informational flow between the two hands, substantiated through neural, temporal, spatial, visual and mechanical (i.e. haptic) coupling (Sleimen-Malkoun *et al.*, 2011). Many studies have uncovered the hand coordination during two basic bimanual controls: *uncoupled independent control*, where the two hands act independently in manipulating two separate objects, and *physically-coupled control*, where the two hands cooperatively manipulate the same object.

Most of this research focuses on the temporal, kinematic or force field adaptation during congruent (i.e. symmetric or in-phase) and incongruent (i.e. asymmetric or anti-phase) uncoupled bimanual actions (e.g. Kelso *et al.*, 1979; Kelso, 1984; Ivry *et al.*, 2004). This research either attempts to illuminate the phenomenon related to the spontaneous synchronisation of the two upper limbs (e.g. Kelso *et al.*, 1979; Marteniuk *et al.*, 1984), or to elucidate how the two hands cooperate to counterpoise certain task constraints or perturbation (e.g. Franz *et al.*, 1991; Franz, 1997; Ivry *et al.*, 2004). These are investigated by exploiting the mechanism for breaking the congruence of bimanual movements, through *decoupling mechanism*: a process that ‘breaks’ the intrinsic tendency of the two hands to synchronise in spatial, temporal and visual domains (see Table 1.1 for summary and examples).

1.2.1 Coupling as a fundamental mechanism

A remarkable observation about two-handed movements is that, unless demanded by the task, humans tend to initiate movements of both arms in tight *temporal* and *spatial* proximity, sometimes with an onset delay of less than 20 ms (Kelso *et al.*, 1979; Franz *et al.*, 1991). As listed in Table 1.1, temporal coupling can be manipulated by changing the frequency and the relative phase of the movement, while spatial coupling can be manipulated by changing the amplitude and direction of the movement.

When studying temporal coupling in humans, researchers mainly use the term *relative phase* ϕ to quantify and characterise the mode of the coupling, which is obtained by calculating the difference in phase angles between both limb motions ($\phi = \theta_{\text{Limb1}} - \theta_{\text{Limb2}}$) (Swinnen, 2002). As illustrated in Figure 1.2, an in-phase movement involves a simultaneous activation of homologous muscle groups, while an anti-phase movement involves a simultaneous activation of non-homologous muscle groups (Kelso, 1984; see Swinnen, 2002, for review). In general, humans show a basic tendency to temporally couple their upper limbs in in-phase ($\phi = 0^\circ$) or anti-phase ($\phi = 180^\circ$) coordination, although robust findings in the literature show that in-phase movement is more stable and accurate than anti-phase move-

Table 1.1 | Mechanism for ‘breaking’ the congruence of a bimanual task. Shown is the desynchronisation/symmetry-breaking mechanism through temporal, spatial and visual domains. The example tasks are extracted from previous studies on (uncoupled) bimanual coordination.

Domain	Example tasks
Temporal	
Frequency	<i>Congruent:</i> two harmonic finger tapping (i.e. 1:1) (Peters, 1977). <i>Incongruent:</i> two finger tapping of non-harmonic rhythms (e.g. 2:3 or 5:3) (Peters, 1977).
Relative phase (ϕ)	<i>Congruent:</i> relative phase between the movements of the limbs is zero e.g. both hands start at the same time (Kelso <i>et al.</i>, 1979); two abduction movements ($\phi = 0^\circ$ vs 0°) of index fingers (i.e. in-phase) (Kelso, 1984) <i>Incongruent:</i> non-zero relative phase, e.g. both hands start at different time; abduction-adduction ($\phi = 0^\circ$ vs 180°) of index fingers (i.e. anti-phase movement) (Kelso, 1984).
Spatial	
Amplitude	<i>Congruent:</i> reaching for objects at the same distance/height (Diedrichsen <i>et al.</i>, 2001); drawing two circles of the same radius (Franz, 1997). <i>Incongruent:</i> one hand reaches for a far object while the other reaches for a nearby object (Diedrichsen <i>et al.</i>, 2001); drawing circles with different radii with each hand (Franz, 1997).
Direction	<i>Congruent:</i> both hands moving towards the same direction; drawing two ‘identical’ circles at the same time (Franz <i>et al.</i>, 1991; Franz, 1997). <i>Incongruent:</i> moving one hand in X direction while the other moves in Y direction (Franz, 1997); drawing a circle with one hand and a line with the other[†] (Franz <i>et al.</i>, 1991; Franz, 1997).
Visual	
Object properties	<i>Congruent:</i> reaching for objects of the same size and shape (Utley <i>et al.</i>, 2004). <i>Incongruent:</i> reaching for a small and a big object (Utley <i>et al.</i>, 2004); lifting a sphere and a cube.
Visual description	<i>Congruent:</i> target box with a written description as the colour of the box itself, i.e. a red box written as ‘RED’. <i>Incongruent:</i> a red box written as ‘GREEN’.
Force	
Magnitude	<i>Congruent:</i> both hands produce the same isometric force (Steglich <i>et al.</i>, 1999). <i>Incongruent:</i> produce isometric forces of unequal intensity (Steglich <i>et al.</i>, 1999).

[†] This type of spatial coupling (different patterns/forms) is considered to be related to parameters of direction (Franz, 1997).

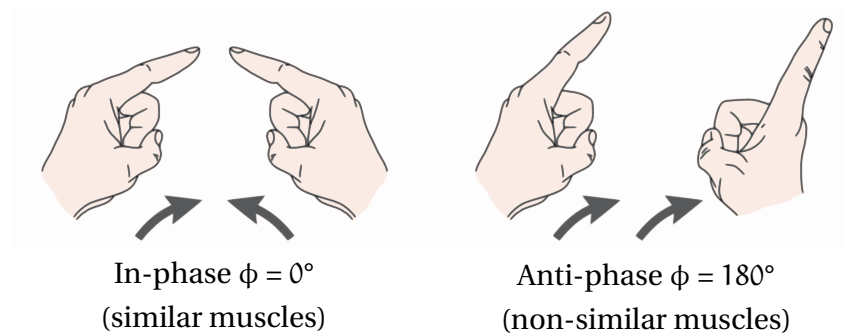


Figure 1.2 | Temporal coupling in bimanual coordination. In general, humans show a preference for activating homologous (similar) muscle groups simultaneously in in-phase movements. Figure adapted from Swinnen (2002).

ment (e.g. Kelso, 1984; Carson, 1995; Semjen *et al.*, 1995). For example, during a repetitive abduction-adduction of the index fingers of the two hands, the human motor system shows a persistent tendency to alter movement coordination from a 180° relative phase movement into a 0° relative phase movement (Kelso, 1984). The tendency to temporally synchronise both hands can be further observed during tap rhythm task with both two fingers moving in non-harmonic relations. In this scenario, most of the time, humans are unable to produce two distinct timing patterns without any interference (Peters, 1977; Klapp, 1979).

Besides the preference to move within a common temporal coupling, human's tendency to synchronise their upper limbs can be observed in the *spatial* domain, too (e.g. Franz *et al.*, 1991; Franz, 1997; see Ivry *et al.*, 2004, for review). Spatial coupling in humans can be observed quite readily in the well-known 'rub the stomach while patting the head' example. An individual who tries to perform this task finds it difficult to decouple the movements of both hands, as the spatial trajectory of one limb tends to bias to the movement of the other. An experimental version of spatial coupling was studied by Franz *et al.* (1991) in a task that involves drawing a line and a circle simultaneously with each hand (Figure 1.3A). Here, both limbs demonstrate natural tendency to synchronise in space, where the drawing of the line was inclined to resemble a circular shape (i.e. elliptical), while the drawing of the circle was compressed to form a line. Similarly, when comparing two circle drawings in in-phase ($\odot - \odot$) and anti-phase ($\odot - \odot$) rotation (Semjen *et al.*, 1995), as well as during three-sided drawings in in-phase ($\square - \square$) and anti-phase ($\square - \square$) (Franz *et al.*, 1996; see Figure 1.3B), the in-phase drawings appear to be more stable than the anti-phase ones. Despite the spatial interference observed in all of these activities, the two hands remain to move on a background with tight temporal coupling, where the frequencies of the movements are similar, and the relative phase maintains at zero.

Despite this tendency to couple both hands, many bimanual ADLs are inherently asymmetric, with one hand – usually the dominant hand – taking an active role while the non-

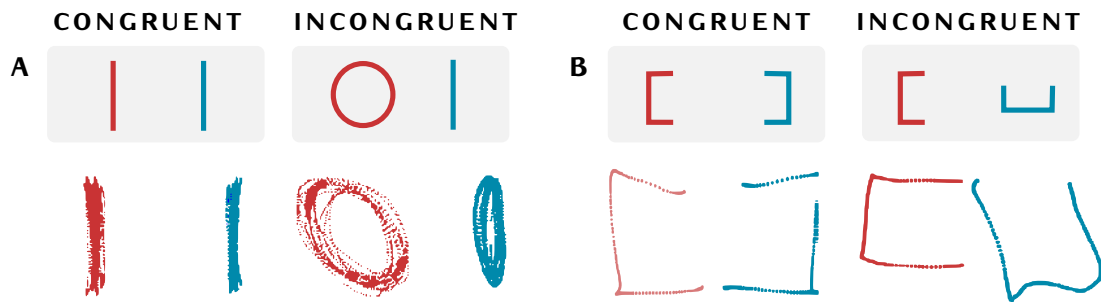


Figure 1.3 | **Spatial interference in two bimanual drawing tasks.** Shown are **A.** a line-line drawing task (in-phase) and a circle-line drawing task (anti-phase) (Franz *et al.*, 1991) and **B.** a mirror symmetric and an asymmetric three-sided square drawing task, where the successive sides are orthogonal (Franz *et al.*, 1996). Figure adapted and modified from Ivry *et al.* (2004).

dominant hand takes a more subservient, supportive role (Yadav & Sainburg, 2014; Schabowsky *et al.*, 2007). The supportive role observed from the non-dominant side is often to hold or steady an object, while the remaining hand manipulates the object, for example, opening a screw-top jar. In this situation, the supportive hand may predict the localised mechanical perturbation induced by the active hand and compensate the perturbation by stabilising it. It can also be observed that in some cases the motor system remains to assign leading-compensatory roles to each hand even when the task appears to be symmetric. One clear example is during the uncapping of a pen, where one hand holds the pen while the other exerts the force to remove the cap. Here, one hand still assumes a leading role despite the symmetric nature of the task.

1.2.2 Neurological correlates of bimanual coupling

A considerable research effort has been devoted to associating a human's sensorimotor behaviour with their neurological correlates. Early studies established a primary role of the *corpus callosum* in bimanual coordination. Consisting of between 200 and 800 million axon fibres, the corpus callosum interconnects homologous cortical areas of the left and right cerebral hemispheres. To coordinate bimanual movements, the corpus callosum integrates information across the hemispheres in a process called *interhemispheric communication* (Bloom & Hynd, 2005). The prominent role of the corpus callosum in mediating interhemispheric communication and bimanual coordination can be observed in callosotomy patients (i.e. surgical removal of the corpus callosum, also referred to as 'split brain'). In this scenario, post-posterior callosotomy patients show no observable interference while performing two incompatible movements with different spatial trajectories, unlike normally observed in pre-callosotomy condition (Eliassen *et al.*, 1999; see Figure 1.4), or in controls¹ (Franz *et al.*, 1996;

¹ The one-patient study by Franz *et al.* (1996) shows a rare finding where callosotomy patient exhibit superior performance relative to controls during a spatially-incongruent drawing task (similar task to Eliassen *et al.*, 1999)

see Swinnen, 2002, for review). Furthermore, the accuracy of in-phase and anti-phase movements of post-posterior callosotomy patient is preserved, despite control subjects typically demonstrating lower accuracy during anti-phase movement relative to in-phase movement (Eliassen *et al.*, 1999). The insignificant effect of anterior callosotomy on the spatial coordination is believed to be due to the anterior corpus callosum being more responsible for controlling temporal coupling instead of spatial. These findings highlight the spatial cross-talk that arise from the exchange of information about the limbs between the two hemispheres, within an intact corpus callosum (Ivry *et al.*, 2004).

Despite the uncoupled spatial coordination, the temporal coupling remains to be preserved in callosotomy patient (Franz *et al.*, 1996; Ivry & Hazeltine, 1999). However, Kennerley *et al.* (2002) noted that this coupling is only preserved in discrete events (such as movement onset). Specifically, during incongruent continuous circle drawing, the circle drawing of callosotomy patients remains uninterrupted and the hands oscillate at two non-harmonic frequencies, indicating temporal uncoupling. To test this finding, Ivry *et al.* (2004) performed two hybrid – continuous and discrete – tapping experiments involving flexion-extension movements of the index fingers. In the continuous condition, subjects were instructed to normally flex and extend their index fingers in a smooth and continuous manner, whereas in the discrete condition, subjects were instructed to insert a brief pause prior to each flexion phase. The authors found that in the discrete condition, the finger movements of callosotomy patients remained to move at a similar frequency. In contrast, in the continuous condition, the two fingers moved at different frequencies and non-zero relative phase; thus endorsing Kennerley *et al.*'s finding that only the temporal coupling of discrete bimanual control, not continuous, is preserved following callosotomy.

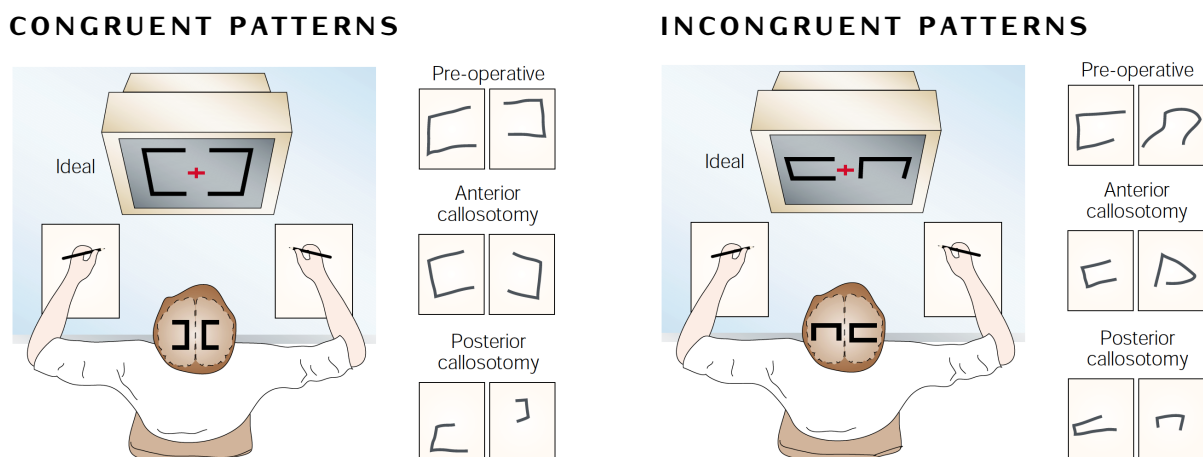


Figure 1.4 | Directional (spatial) interference in pre- and post-anterior and posterior callosotomy. Shown are the results from a one-patient study by Eliassen *et al.* (1999) during congruent (in-phase) and incongruent (anti-phase) bimanual drawing task, investigated during pre-operative and post-operative anterior and posterior callosotomy. Figure adapted from Swinnen (2002).

1.2.3 Functional role of feedback

Early studies on sensory influence established the dominance of the vision system when exploring objects with both hands (Rock & Victor, 1964), although it is now commonly accepted that both haptic and visual sensory channels are weighted based on their reliability and appropriateness (Helbig & Ernst, 2008). For instance, Contu *et al.* (2016) showed how humans synergically exploit both visual and haptic information when performing bimanual manipulation tasks, during a bimanual grasp and reach task under four different conditions: no feedback, visual only, haptic only, and haptic + visual combined conditions. The study revealed an improved performance during the haptic only condition, and haptic + visual condition, compared to the no feedback condition and visual only condition, suggesting that haptic feedback plays a significant role in facilitating bimanual object manipulation.

Nevertheless, the feedback control mechanism in bimanual coordination is highly task-dependent. A change in bimanual control strategy can be observed when comparing the bimanual manipulation of one shared objects instead of two, even if both hands are *virtually-coupled* instead of mechanically-coupled. For instance, Diedrichsen (2007) compared hand movement strategy during a single cursor task with a two-cursor task (Figure 1.5). In the one-cursor task, subjects moved a single cursor displayed at the spatial midpoint between the two hands (solid black circle) to a single, shared target (white circle), while in the two-cursor task, subjects moved the two cursors to two separate targets. In both tasks, a mechanical perturbation was applied to the left hand (dashed black arrow). The results revealed that in the two-cursor task, the mechanical perturbation to one hand caused a feedback correction in only the perturbed hand (red arrow). In contrast, the mechanical perturbation to one hand prompted a response in both perturbed (red arrow) and unperturbed (blue arrow) hands in the one-cursor task. Since such response was independent of actual visual feedback from the cursor, the distinctive control strategies implies that the integration of sensory information during bimanual control is (optimally) modulated to fit current task demands.

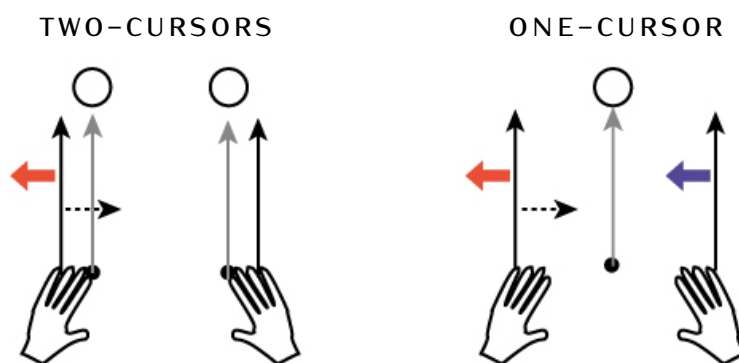


Figure 1.5 | **Optimal task-dependent changes in bimanual feedback control.** Figure adapted from Diedrichsen (2007).

1.3 DEVELOPMENT OF SENSORIMOTOR CONTROL FROM INFANCY TO ADULthood

Humans' sensorimotor skills develop with the maturation of the sensorimotor cortex, and this development is most rapid throughout the first two to three years of life. The success of these manual skills in daily life requires a complex process that incorporates a person's attention, cognition, motivation, perception, sensorimotor system and musculoskeletal system, which is developed through intensive practice and repetitive trials (Eliasson, 2005). This requirement is true even for a seemingly simple task such as picking up a small object using thumb and index finger. This movement, commonly referred to as the *precision grip*, requires young children to learn to calibrate the 'just right' grip force needed in order to hold and manipulate an object without dropping or crushing it. The skill for coordinating the 'just right' grip force improves as one's sensorimotor system matures, and the development of precision grip control has been of particular interest for researchers to understand how a child's sensorimotor system progresses from infancy to adulthood (Westling & Johansson, 1984; Forssberg *et al.*, 1991). Given the prominence of this skill in portraying the typical development of sensorimotor control, this section discusses the process of mastering the precision grip as an example for understanding the development of manual skills from infancy to adulthood.

1.3.1 Critical period for sensorimotor progression in developing brain

Throughout a lifespan, *stimulation* and *experience* play a significant role in determining the physical structures of our brain, and are thought of as the key components responsible for maximising neural connections and brain development (Rosenzweig, 1984). Brain development is a multifaceted process and much of what we know about how stimulation and experience influence the development comes from studying animals. Animals that are raised in stimulating environments with many toys and companions to play with develop brains that have more synapses and are physically heavier than animals who grow up in non-stimulating, standard laboratory conditions. Likewise, the brain of animals raised in stimulating environments and moved to non-stimulating standard laboratory conditions lose neural connections (Grossman *et al.*, 2003). This is true for humans, too; under-stimulated infants, including those who experience child mishandling or who are brought up in a deprived environment such as in poor, understaffed orphanages, show severe cognitive and perceptual deficits compared to children who are raised in family environment (Chisholm, 1998).

Infants are equipped to respond to the stimulation they encounter in the world, such as touch, light, and sound, and to adapt through the use of their reflexes. Each of these re-

flexes has its own developmental course. Stimulation and experiences trigger neurons in the cerebral cortex of a developing brain to form multiple connections with other neighbouring nerve cells, called *synapses*. As visualised in Figure 1.6, interneuron synapses proliferate rapidly during the first two years following a full-term birth, forming the information processing networks that are responsible for all of our thoughts, sensations, feelings and actions (Corel, 1975). By the age of 2 years, the brain forms twice as many synapses as it will have in adulthood. The period during which the interneuron synapses proliferate reflects *the crucial period for neural development*, which typically occurs between birth to the first 2 to 3 years of life, when the development of sensorimotor skills is most rapid (Uylings, 2006; Anderson *et al.*, 2011). In fact, the critical period emerges even before birth, as it was discovered that the sensorimotor system matures rapidly yet systematically from pre-term (i.e. mid- to late-third trimester) to full-term babies, and this maturation is significantly influenced by experience (Allievi *et al.*, 2016). However, although infancy is a particularly important time for the formation and strengthening of synapses, brain development continues into emerging adulthood, until it matures roughly in mid-twenties (Rosenzweig, 2002).

At all ages, the human brain can change its organisation and function in response to experience: a remarkable property of the nervous system that is often referred to as *plasticity* (Kolb *et al.*, 2003). Although the cortical organisation is already determined by 6 months of gestation (Dall’Orso *et al.*, 2018), the brain is most plastic during the first few years of life (Nelson *et al.*, 2007). A developing brain is capable of reorganising itself in response to injury in ways that an adult’s brain cannot. Adults who suffered brain injuries during infancy or early childhood often have fewer cognitive difficulties than those who were injured later in life. However, an immature young brain – although more plastic – is also more vulnerable to injury, which can result in the development of cerebral palsy (Uylings, 2006; Johnston *et al.*,

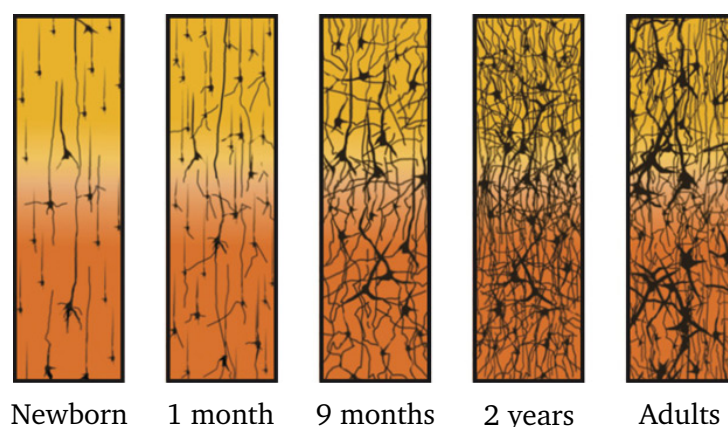


Figure 1.6 | The density of interneuron synapses in the cerebral cortex develop rapidly over time. By the age of 2 years, the brain forms twice as many synapses as it will have in adulthood. The ‘overproduced’ connections are gradually eliminated throughout childhood and adolescent through *pruning* process. Figure adapted from Corel (1975).

2009). As such, if an injury occurs to a part of the brain during a critical point in neural development, the sensorimotor capacity that is linked to the affected region will be irreversibly impaired (Luciana, 2003). The ability of a young child's brain to compensate for an injury depends on the age at the time and the site of injury, as well as the sensorimotor capacities the injury comprises. The brain is most plastic when neurons are forming many synapses; however, brain injuries sustained before 2 to 3 years of age is associated with more severe, and long-lasting deficits than injuries sustained later in childhood (Anderson *et al.*, 2005), suggesting that a reserve of neurons is needed for the brain to show plasticity. The extent to which an individual can recover from a brain injury depends on the nature and severity of the injury, age, experiences after the injury, and the intervention following an injury (Anderson *et al.*, 2011).

1.3.2 Mastering manual skills: precision grip

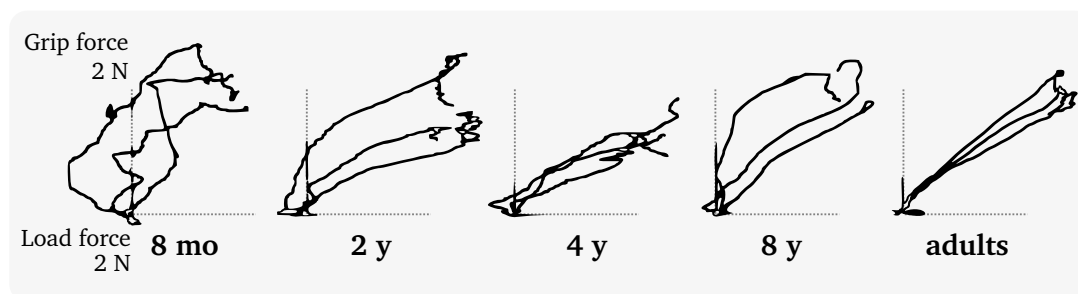
The development of sensorimotor function from infancy to adulthood can also be observed from the progress of a human's manual skills. In TD children, there is an initial rapid emergence of motor skills over the first two years of life, in concert with their neurological development. Such skills continue to refine for several years until they attain a mature functional control in the early teenage years. Force coordination is poor in babies; for instance, a one-year-old child will probably squish a piece of bread before even eating it, whereas a two-year-old toddler can manage to hold bread quite well. The motor output becomes more coordinated and less varied in 4-year-old children, where children of this age are typically able to scale and anticipate their force output more efficiently, which can be observed when manipulating something delicate, such as handling a kitten. Nevertheless, anticipatory scaling with an object's physical properties, such as weight, size, and compliance, is not developed until the age of 6 to 8 years; and will only fully mature and become adult-like between the age of 10 to 12 years (Eliasson, 2006).

Amongst the very first studies that explored the development of sensorimotor control of grasping in children is by Forssberg *et al.* (1991). The main parameter investigated in this study is the *grip-lift synergy* (Johansson & Westling, 1990): a simple yet powerful measure for assessing the adaption of grip force based on environmental demands (e.g. object's friction, size, weight). Forssberg *et al.* (1991) found the grip-load synergy becomes more linear with age (see Figure 1.7A), indicating that this synergy is not innate. As such, adults and older children generate grip forces in parallel with load forces during the loading phase (i.e. before the lifting movement starts). In contrast, younger children, particularly those four years and younger, are typically unable to coordinate grip and load forces in parallel due to their immature sensorimotor control. Instead, these two forces are generated in sequence. Fur-

thermore, as visualised in Figure 1.7B, the force rate profile of younger children is irregular and multi-peaked, while older children and adults demonstrate a bell-shaped force rate profile: indicating an efficient adjustment of grip force to the weight of an object and refined anticipatory control.

A mature anticipatory control requires the nervous system to fully utilise sensory feedback to predict, integrate, and store information concerning the internal/memory representation of an object's physical properties. In the second part of Forssberg *et al.* (1992)'s study, which investigated the development of anticipatory control amongst 100 children between the age of 1 to 15 years, the authors observed that the emergence of an anticipatory strategy was only evidenced between the age of 8 and 11 years. Here, the youngest subject demonstrated a strikingly poor anticipatory control and required longer time during preload and loading phases than the older subjects. The observed poor coordination is a characteristic of immaturity, likely attributable to the underdeveloped motor output and sensory processing in younger children (Eliasson *et al.*, 1991).

A. GRIP-LOAD SYNERGY



B. GRIP FORCE RATE - LOAD FORCE PROFILE

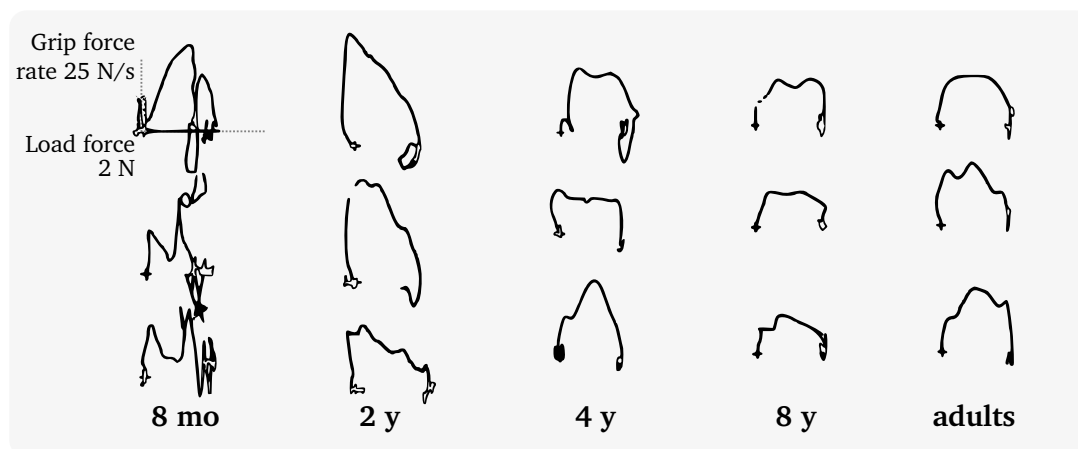


Figure 1.7 | Grip-load synergy and grip force rate-load force profiles in children and adults. Three trials are displayed for each subject. Figure adapted and modified from Forssberg *et al.* (1991). mo, months; y, years.

1.4 BIMANUAL COORDINATION IN UNILATERAL SPASTIC CEREBRAL PALSY

Bimanual skills for TD children start to emerge as early as three months old. At this stage, infants use gross symmetrical bilateral skills, such as banging two balls together or reaching for toys with both hands moving simultaneously. As their sensorimotor function develops, at the age of 6 months, they begin to learn to stabilise an object with one hand while the other hand explores or manipulate it. The holding pattern at this stage can be without grasp, such as anchoring the paper while drawing, or with grasp, such as opening a drawer while the other hand places an object inside the drawer. Later, between the age of 24 months to 36 months, children continue to develop their competency to cooperate their hands together to perform more complex tasks such as tying shoelaces or stringing beads (Case-Smith, 2006).

As discussed in the previous section, an injury to any part of the brain during the critical period of brain development may lead to life-long impairment to movement and posture — a condition commonly referred to as *cerebral palsy* (CP). CP is the most common, non-progressive brain injury that affects 1 in every 400 live births worldwide (Disability Charity Scope UK, 2018). According to Rosenbaum *et al.* (2007), CP is defined as “(...) a group of permanent disorders of the development of movement and posture, causing activity limitations, that are attributed to non-progressive disturbances that occurred in the developing foetal or infant brain”. Brain injuries that lead to CP can occur before, during or shortly after birth, and variations in the time course, lesion locations and associated symptoms requires a heterogeneous classification system (see Appendix A various classifications of CP).

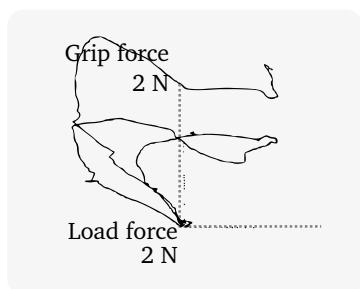
Unilateral spastic CP (USCP) is a subtype of CP caused by a unilateral brain lesion, which results in motor impairment to the contralateral side of the body, with upper limbs usually more severely affected than the lower limbs (McManus *et al.*, 2006). Children with USCP, also referred to as ‘*hemiplegic CP*’, typically present with persisting disabilities that are frequently rooted in the neurodevelopmental impairments related to their sensory, perception, cognition, communication and behavioural functions (Rosenbaum *et al.*, 2007). These neurodevelopmental impairments are directly caused by their motor deficits as a result of CP, such as increased muscle tone, muscle weakness, decreased range of motion, slowness, impaired selective motor control, and coordination difficulties (Brown *et al.*, 1987). Functional difficulties are generally more significant on the affected side of the body, with subtle deficits occasionally observed on the non-affected side (Gordon *et al.*, 1999).

1.4.1 Sensorimotor impairments

Impairments to sensorimotor function amongst children with USCP affect their ability to develop fine motor skills to manipulate objects with accuracy and precision, even during a simple task such as prehensile lifting. As visualised in Figure 1.8, children with USCP demonstrate a highly uncoordinated grip-load synergy that is similar, or even worse than one-year-old TD children (Eliasson *et al.*, 1991; see Forssberg *et al.*, 1991, for comparison). The parallel grip and load force generation is rarely seen in children with USCP. Instead, these two forces develop sequentially, where the grip force increases before the load force. Consequently, these children do not produce a bell-shaped force rates profiles, but rather in step-wise and irregular profiles, with extreme variation between one lift and another (see also Forssberg, 1999). Besides the disturbed coordination of grip-lift, children with USCP also exhibit excessive grip force (Eliasson *et al.*, 1995; Gordon *et al.*, 1999), impaired anticipatory control prior to grip scaling (Gordon & Duff, 1999; Mutsaerts *et al.*, 2006), and prolonged or uncoordinated object release (Eliasson & Gordon, 2000; Gordon *et al.*, 2003) during precision grip.

Accurate sensory information from fingers is essential to adjust the grip to the physical properties of an object, especially the weight and the friction, and the importance of this information is readily observable when one removes the glove to gather change from a pocket. However, children with USCP have reduced sensation in hand, and as a result, these children generally have difficulty in generating the ‘just right’ grip pattern needed for manipulating unfamiliar objects (Eliasson *et al.*, 1991). The four most common sensory impairments found in USCP include tactile perception (the ability to perceive information from pressure and lateral movements against the skin), tactile sensibility (the ability to differentiate information through the sense of touch), stereognosis (the ability to perceive and recognise the form/shape of an object using only tactile information) and proprioception (i.e. kinaesthesia, the ability to perceive body position and movement) (Krumlinde-Sundholm & Eliasson, 2007).

GRIP-LOAD SYNERGY



GRIP FORCE RATE - LOAD FORCE PROFILE

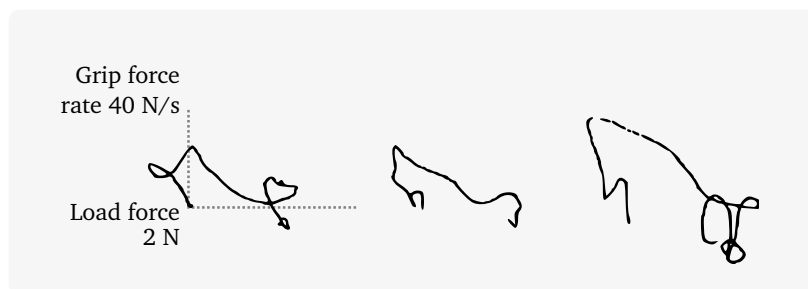


Figure 1.8 | Grip-load synergy and grip force rate-load force profiles of children with USCP. The coordination is worse than that of one-year-old non-disabled children (cf. Forssberg *et al.* (1991); see Figure 1.7). Figure adapted and modified from Eliasson *et al.* (1991).

Generally, sensory problems cause issues related to the awareness of the impaired arm and hand. For example, some children demonstrate little awareness that they own five digits on each hand, while some are unaware of the different areas on their palms (Eliasson, 2006). Gordon & Duff (1999) illustrated the critical importance of tactile functioning in an object grasping and lifting task and highlighted how sensory impairments have dampened the day-to-day activities of children with USCP. They stated that: “(...) the impairment in grasping in children with hemiplegic CP (i.e. USCP) are largely but not exclusively due to disturbed sensory mechanisms which may have direct implications for therapeutic intervention” (Gordon & Duff, 1999, p. 586). Consequently, children with USCP typically developed strategies to compensate for their sensory deficits, such as prolonging the duration between movement phases or exerting an excessive amount of force when grasping an object in order to amplify the sensory feedback.

1.4.2 Bimanual impairment

The impairment to bimanual coordination amongst children with USCP is generally more severe than their unilateral impairment (Gordon *et al.*, 2007). Research on the bimanual coordination of children with USCP has predominantly focused on discrete bimanual tasks, such as drawer opening (Hung *et al.*, 2004), object reaching and grasping (Sugden & Utley, 1995a; Steenbergen *et al.*, 1996; Utley & Sugden, 1998; Steenbergen *et al.*, 2000), and simple lifting task (Utley *et al.*, 2004; Steenbergen *et al.*, 2008; Islam *et al.*, 2011). In contrast, bimanual cyclical tasks such as congruent and incongruent drawing have received much less attention (Fagard *et al.*, 2001; Volman *et al.*, 2002).

Sugden & Utley (1995b) was amongst the first study that investigated two-handed coordination in USCP, where they examined the qualitative performance during functional bimanual tasks, such as flask opening, removing cello-tape and bead threading. The study found that bimanual tasks improved the fluency of the affected side through facilitation from the non-affected side. They concluded that such findings are an indication that “the human motor system can be self-organised to adapt to constraints placed upon it” (Sugden & Utley, 1995b, p. 78). Sugden & Utley (1995a) extended their study to investigate the upper limb kinematic of children with USCP, and found that every child demonstrates a temporal and spatial interlimb coupling pattern during bimanual movements. Furthermore, the delay between hands was reduced by 50% during bimanual reaching and grasping task when compared to an equivalent unimanual task. Similarly, Steenbergen *et al.* (1996) observed a 92% decrease in asymmetry and delay between hands during a similar bimanual reach-to-grasp task compared to a unimanual equivalent, supporting the findings of Sugden & Utley (1995a) which suggested that bimanual movements encourage “a coordinative structure type of con-

trol in which both arms are constrained to act as a single unit, thereby enhancing control” (Steenbergen *et al.*, 1996, p. 97). The coordination of reaching and grasping amongst children with USCP was further studied in Steenbergen *et al.* (2000), where the research team investigated the inter-segmental coupling between elbow and shoulder joints during reaching and grasping movement using different speed conditions. The study found that during bimanual movement, the unaffected hand ‘mimicked’ the kinematics of the affected hand, in term of peak velocity, mean velocity and the number of zero crossings in the acceleration profile.

In the last two decades, bimanual coordination research amongst children with USCP has widened to include asymmetrical tasks. For instance, Volman *et al.* (2002), whom examined hand performance during a two-circles drawing task, observed a decrease in the temporal variability and an increase of smoothness of circle drawing during a symmetrical bimanual task compared to a single-handed task. In contrast, asymmetrical drawing of two circles resulted in an increase of spatial and temporal variability in the unimpaired arm. Similarly, Hung *et al.* (2004) studied the coordination pattern during a drawer opening and an activate switch task, where the coordination of the two hands was examined under two conditions: self-paced condition and ‘as-fast-as-possible’ condition. The study found that during the self-paced trial, the movement of USCP was slower and less coordinated than TD children. Interestingly, children with USCP demonstrated improved bimanual coordination under the sped-up condition, in comparison to the self-paced condition.

Besides reach to grasp movements and bimanual drawings, children with USCP also have difficulties to adjust their grip forces based on environmental demands (e.g. the size, weight and the compliance of an object). As observed during unimanual tasks, anticipatory control is severely impaired in children with USCP, due to the sensory deficit on the involved hand. However, Gordon *et al.* (1999), who studied the coordination of grip force during a congruent bimanual lifting task, discovered that children with USCP could utilise the sensory information from the non-involved hand to anticipate the scaling of isometric force for improving the quality of subsequent lifts of the involved hand. Islam *et al.* (2011) extended the study by examining grip force coordination during an incongruent task, where each hand performed different movement during a prehensile lifting task. The study observed no similar facilitation of the non-involved side between subsequent lifts (cf. Gordon *et al.*, 1999), as the temporal coordination and scaling of the grip force remain impaired throughout all trials. Surprisingly, the authors also discovered that incongruent task significantly impeded the movement of the non-affected side, where the non-affected side slowed down to match the movement speed of the affected side.

1.4.3 Bimanual-based rehabilitation

Rehabilitation strategies for children with USCP have adopted a multitude of activities into their framework, where two of the most practised and effective treatments are the constraint-induced movement therapy (CIMT) (e.g. Taub *et al.*, 2004; Eliasson *et al.*, 2005; Gordon *et al.*, 2006b) and bimanual interventions (Charles & Gordon, 2006; Gordon *et al.*, 2007). CIMT is based on the work of Taub *et al.* (2004), who identified the issue with *developmental disregard* (also commonly referred to as ‘learned non-use’), which refers to the lack of the use of the affected side amongst children with USCP. Specifically, affected individuals have some ability to use the affected side, but find controlling it to be more difficult, therefore use the side less. Prolonged developmental disregard limits hand dexterity to a poor, unrefined level, especially in tasks that involve the use of both hands. During CIMT, the non-affected hand is restrained, so as to passively induce the practice of affected hand (Figure 1.9). Besides ‘forcing’ greater use of the affected side, the implicit assumption underlying predominantly unimanual approaches such as CIMT is that improving the affected hand will automatically translate to the improvement of bimanual control and coordination.

However, skills acquired during unimanual practice may not necessarily transfer to bimanual coordination (Nozaki *et al.*, 2006; Yokoi *et al.*, 2017). Furthermore, unlike adults with unilateral stroke who only need to (re)-train their bimanual skills, children with USCP may have never learned how to use their impaired extremity. Therefore, the skills they acquire during practice with CIMT may not necessarily apply to bimanual context, as most of them will need to learn the skills for the first time.

Training the functional independence of a developing child should integrate the use of both hands in cooperation, as such ability might be best accomplished by directly practising bimanual skills (Gordon *et al.*, 2007). Therefore, bimanual-based interventions, such as the hand-arm bimanual intensive therapy (HABIT) (Charles & Gordon, 2006), were developed to address the limitation of CIMT. HABIT is geared towards encouraging the development of the motor skills of these children, besides facilitating the functional use of the more impaired limb by moving both arms together. Practice with HABIT incorporates three key components: (1) increase of task difficulty, (2) practice of component movements that are part of a more complex task and (3) training of functional goals. The upper limb activities performed during HABIT include card games, video games, and arts and crafts (Gordon *et al.*, 2007). While both CIMT and bimanual training were found to improve dexterity and bimanual upper extremity use, the bimanual training may allow a more direct practice of functionally meaningful goals than a unimanual practice (Gordon *et al.*, 2011). Therefore, as suggested by Gordon *et al.* (2007), bimanual therapy is best practised as a complementary tool to CIMT.

Theoretically, rehabilitation training through bilateral activities provides an effective means of regaining the upper limb function of individuals affected with bimanual deficits. Advanced justifications for bilateral training rely on three main arguments: (1) the existence neurally-mediated coupling between limbs (reviewed in Swinnen, 2002; Carson, 2005), (2) the evidence that skilled bimanual training drives neural plasticity (e.g. Friel *et al.*, 2016; Debaere *et al.*, 2004), and (3) that bimanual training is closer to everyday tasks than unimanual practice, as most of our ADLs, such as bathing, dressing and feeding require the use of both arms. Therefore, bilateral training could be the most effective method to train or regain the functional activities and independence of individuals with bimanual deficits (McCombe Waller & Whittall, 2008).

However, despite the expected benefits, evidence for the functional efficacy of bilateral training (relative to standard care) amongst children with USCP are *modest* at best (Sakzewski *et al.*, 2014). A recent systematic review by Tervahauta *et al.* (2017) has even concluded that the effectiveness of bilateral training over CIMT is somewhat *inconclusive*. Thus, how bilateral training could be utilised to its maximum capacity and how children with USCP could benefit from bilateral training remain largely unclear.

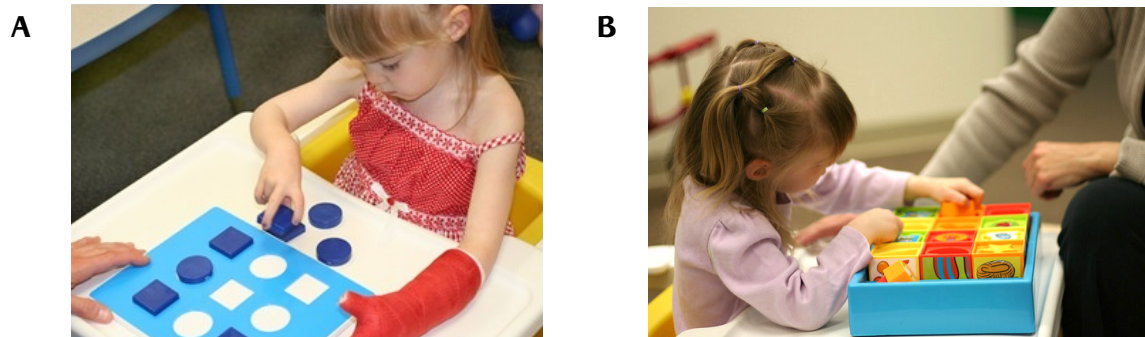


Figure 1.9 | CIMT and HABIT, two of many rehabilitation options for USCP. Shown are **A.** the constraint-induced movement therapy (CIMT) and **B.** the hand-arm bimanual intensive therapy (HABIT). During CIMT, the non-affected hand is constrained, thus ‘forcing’ patients to use the affected hand during prescribed tasks. In contrast, HABIT incorporates the simultaneous use of both hands. Pictures courtesy of Affectionately Yours².

² Photos reprinted with permission, courtesy of Melanie Fraase from Affectionately Yours. URL: <https://www.flickr.com/people/36076980@N05/> [Accessed on 30-08-2018].

1.5 POTENTIAL OF VISUAL AND HAPTIC COUPLING FOR UNILATERAL SPASTIC CEREBRAL PALSY

The lack of observable efficiency of bimanual training over standard care attests to the need for a more comprehensive understanding of the coordination of upper limbs as a whole. In fact, to date, bimanual coordination studies on basic motor control and clinical interventions for children with USCP have progressed without a common guided taxonomy and inventory of bimanual movements — a similar problem to research on unilateral stroke patients (Shirata *et al.*, 2016; Kantak *et al.*, 2017). The lack of comprehensive inventories bridging every investigated bimanual task in motor control studies and how it can be applied into clinical interventions poses an important limitation in the scientific progress of behavioural, neurophysiological and clinical assessment of bimanual deficits in USCP. Therefore, as illustrated in Figure 1.10, this thesis proposes a comprehensive inventory of bimanual actions that classifies two-handed tasks, based on the properties of the task. The properties include the number of objects involved, the nature of the coupling between the hands, and the similarity of the task's demands on each hand.

Based on the proposed inventory, it is apparent that there is a lack of studies concerning the coordination of physically-coupled bimanual movement, as most research has focused on the uncoupled aspect of bimanual actions alone. As defined at the beginning of this chapter, physically-coupled bimanual control involves manipulating a single mutual object or two connected objects. The 'physical coupling' between the two hands can be instituted in the form of a *virtual connection* (external to the body, e.g. controlling, in a video game context, a single virtual object or two virtual but connected objects using both hands) or a *mechanical connection* (e.g. moulding a snowball). During a mechanically-coupled task, haptic feedback is yielded in the form of opposing forces generated by each hand. In contrast, visual feedback is yielded in the form of visual attention onto a single shared object during coupled tasks, instead of onto multiple objects during uncoupled tasks.

The limited studies on physically-coupled bimanual control leave the potential benefits of incorporating naturalistic *visual* and *haptic* feedback in physically-coupled hand movements under-explored. The capacity of visual feedback alone has been investigated amongst children with USCP, where a specific manipulation of visual feedback was introduced in the form of a 'mirror box' illusion (e.g. Smorenburg *et al.*, 2013; Adler *et al.*, 2015). Mirror box movement, as the name suggests, is carried out by placing a glass screen, an opaque screen or a mirror ('mirror box') between the arms. The mirror box provides visual feedback of a no lag, symmetric movement between the two arms corresponding to the movement of the unimpaired arm alone. The hope is that this perception could potentially facilitate movement of

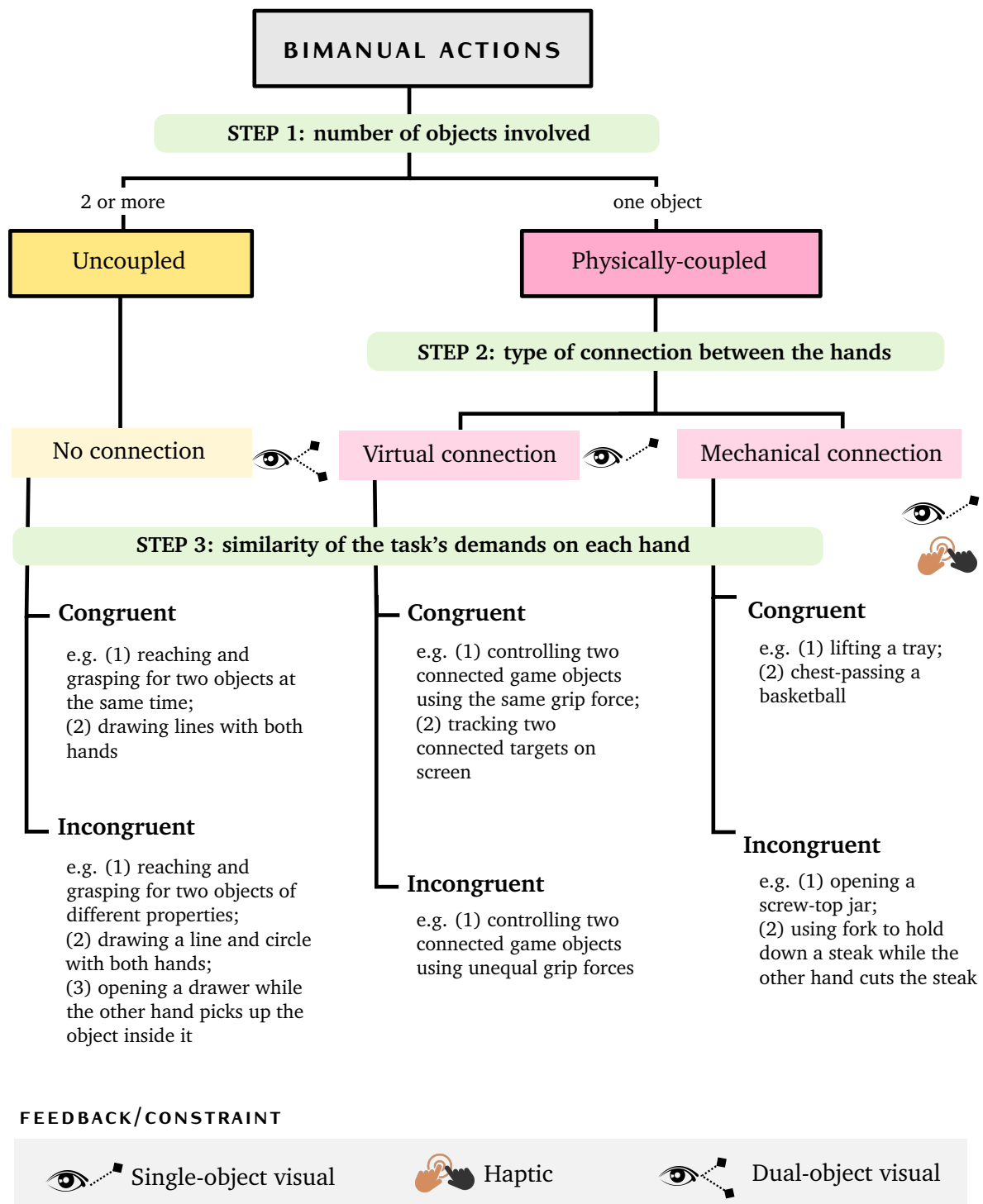


Figure 1.10 | Proposed classification of bimanual actions based on task properties: the number of objects involved, the nature of the coupling between the hands, and the similarity of the task's demands on each hand. Uncoupled tasks involve only temporal and spatial couplings with no virtual or mechanical connections between the hands. Physically-coupled tasks involve either a virtual or a mechanical connection between the hands. Mechanically-coupled bimanual tasks yield haptic feedback in the form of forces that relay between two opposing hands.

the impaired arm. However, studies have revealed contradictory findings on the benefits of mirror box training. Smorenburg *et al.* (2013) for instance, showed significant improvement in the accuracy of the affected hand when conducting mirror movements, whereas a more recent study by Adler *et al.* (2015) found that mirror box movement had an adverse effect on the coordination and timing of both hands during ADLs.

Apart from mirror box illusion, there has been no further investigation into ‘shared’ visual feedback during bimanual control tasks. Manipulating a single object bimanually – be it through a virtual or mechanical connection – could redirect visual attention from multiple objects (in uncoupled tasks) to a shared object thus reducing cognitive load (Franz & McCormick, 2010). Given the cognitive impairment sometimes observed in children with USCP (Rosenbaum *et al.*, 2007), drawn attention to the shared object could potentially reduce cognitive burden induced by uncoupled bimanual tasks.

Furthermore, there is a growing body of research that suggests the benefits of haptic feedback during bimanual coordination of the upper limbs. However, such benefits for children with USCP is yet to be confirmed. Intuitively, the ‘forced use’ of the impaired arm, where it is mechanically- and visually-coupled with non-affected arm, will often (1) invoke the natural tendency to synchronize movement of both hands similar to when the hands are spatially or temporally coupled, and (2) prevent developmental disregard that is commonly observed in USCP. Furthermore, considering that redundant information obtained by both hands could improve haptic estimates (Iyengar *et al.*, 2007), it is possible that for children with USCP, performing a haptically (i.e. mechanically)-coupled task could off-load processing of cutaneous and kinaesthetic information to the ipsilateral side, through coordinated force transfer between the hands and the object. The same forces would not be transferred between the limbs when exploring two independent objects alone. Intuitively, this ‘ipsilateral strengthening’ of sensorimotor activation could help children with USCP compensate for their impaired sensory function, thus facilitating their anticipation of the ongoing movements.

1.6 RESEARCH APPROACH AND THESIS STRUCTURE

An incomplete understanding on the coordination of bimanual movement in general limits rehabilitation progress for individuals with bimanual deficits like USCP. Therefore, this thesis aims to expand the knowledge on the coordination of bimanual movements, by exploring the potential of physically-coupled bimanual manipulation. Specifically, this thesis exploits naturalistic visual and haptic feedback in physically-coupled bimanual movement. The influence of these feedback components is investigated on TD children, children with USCP and healthy adults. The framework developed within this thesis conceptualises the bimanual ‘physical connections’ in a hierarchical manner. This is achieved by developing specific tasks with varying physical coupling, ranging from activities involving bimanual coupling that is purely visual, to activities that nurture haptic interaction between the hands — as listed in Figure 1.11.

To quantitatively assess the functional capacity of subjects performing physically-coupled bimanual tasks, this thesis utilises two custom-made sensor-based devices and a robotic in-

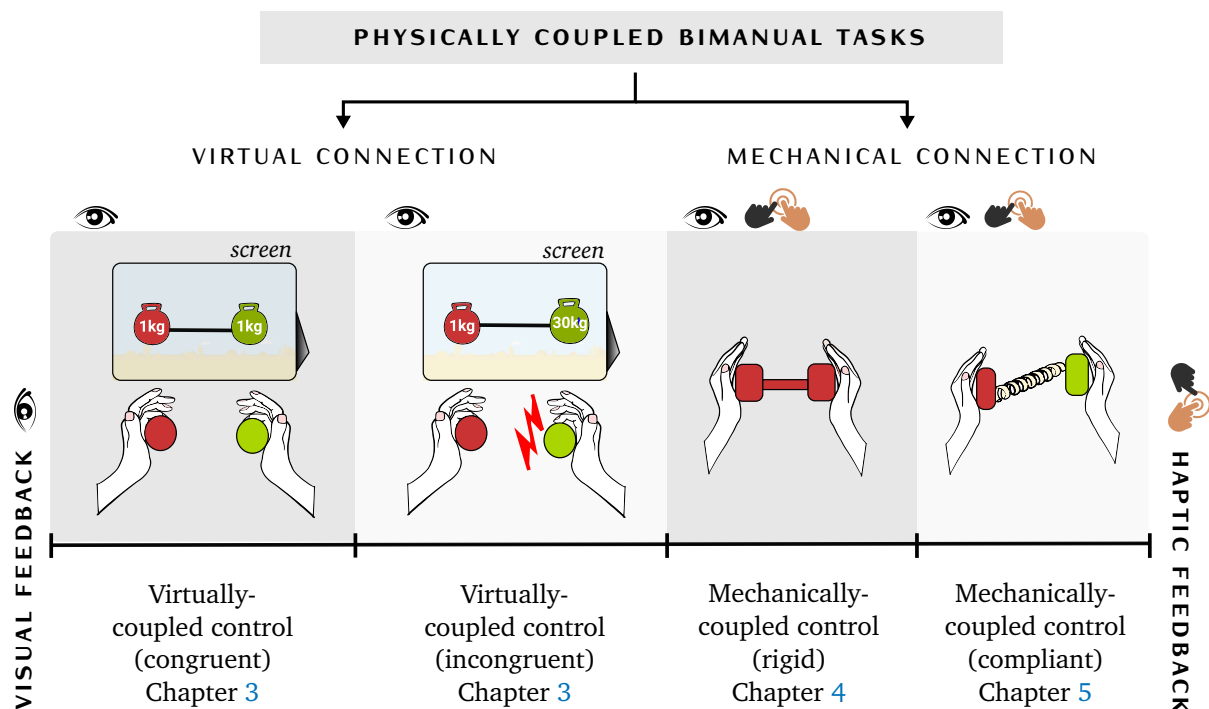


Figure 1.11 | The range of physical coupling during bimanual manipulation. Shown are four different physically-coupled bimanual tasks that will be studied within this thesis. The first task is a virtually coupled task where both hands control a virtual object congruently (no haptic interaction between the hands). A perturbation was added to the second task to induce an incongruent grip control. The third task exploits the haptic potential of physically-coupled tasks, by instituting a mechanical connection between the two hands. The last task investigates the bimanual control while performing tasks with different haptic strengths between the two hands.

terface, which are described in detail in *Chapter 2*. The first device is a bespoke, highly sensitive handgrip device equipped with a force sensor. The device is used with a video game developed specifically to measure grip forces while both hands are virtually-coupled, which is used in the study in *Chapter 3*. The second device is a sensorised cube-shaped toy designed for measuring the grasp forces from two mechanically connected hands, used for the study in *Chapter 4*. The last device is a dual-wrist robotic interface that allows users to program the robot to mechanically couple/uncouple the hands or to change the stiffness of connection between the hands, used for the study in *Chapter 5*.

Four different tasks are delineated within this thesis (see Figure 1.11). Each of these tasks were selected and arranged in the way to sequentially uncover the exploitation of visual and haptic feedback during physically-coupled bimanual movement: First, *Chapter 3* presents a study on the coordination of the hands during unimanual vs. visually-coupled bimanual grasping tasks in neurologically healthy adults, TD children and children with USCP. Then, the visual control strategy of a shared object is further explored by investigating the subjects' control strategy when one hand is perturbed. Specifically, each hand is required to produce unequal grasp forces to control the shared object.

Chapter 4 explores the potential of haptic feedback component provided by physically-coupled tasks, by investigating the coordination of two-handed movement during a real object lifting task. The focus of this chapter is on the performance difference between TD children and children with USCP, as well as on the performance of children with USCP with previous literature that implemented the same protocol during a unimanual task. The benefits of haptic information for children with USCP are also discussed in detail.

Chapter 5 extends the study from *Chapter 4* by investigating bimanual coordination when both hands are connected to varying degrees of coupling stiffness. Specifically, this chapter explores how healthy adults alter their hand movement and grasp force when the haptic connection between the two hands is weak.

Chapter 6 gives a general discussion of the research findings, alongside conclusions and possible future work.

2 | TOOLS FOR STUDYING PHYSICALLY-COUPLED BIMANUAL COORDINATION

This thesis aims to investigate bimanual coordination during physically-coupled tasks amongst TD children, as well as children with USCP¹. As outlined in the introduction chapter, a physical coupling between the two hands can be instituted in the form of a visual and mechanical connection. This chapter introduces the devices and robotic interface used to institute such connections. Based on the output from these systems, a number of metrics were developed to provide a more sensitive and accurate method for measuring bimanual coordination.

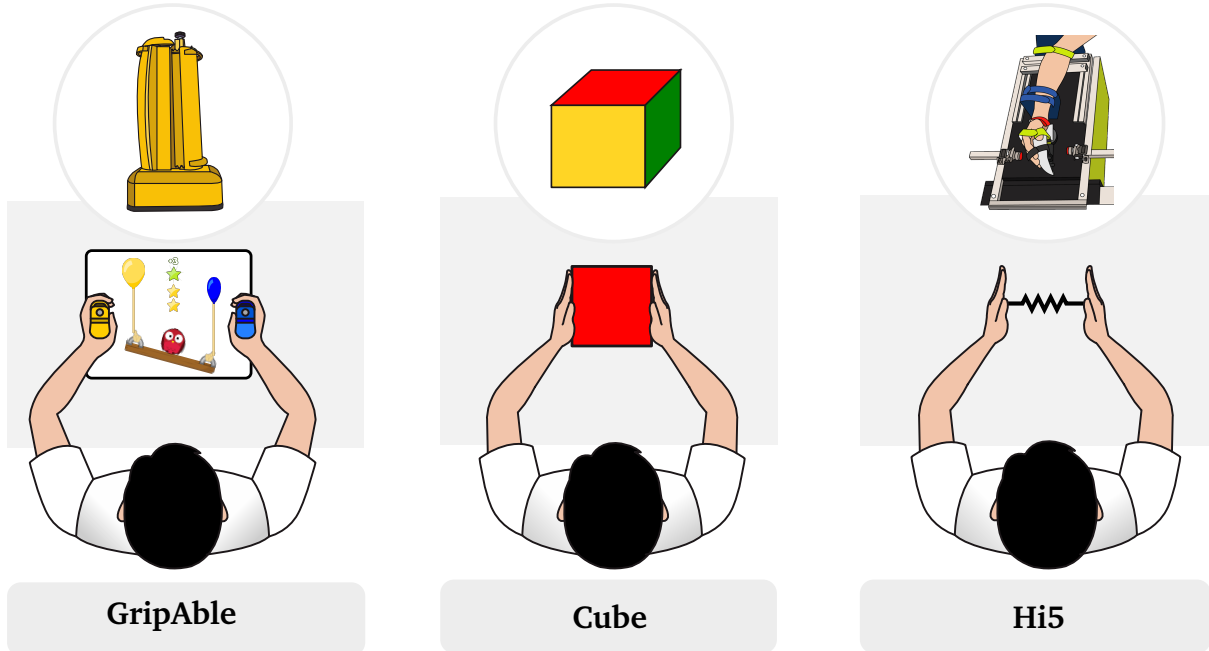


Figure 2.1 | **The devices used for studying physically-coupled bimanual coordination.** Shown are the GripAble, used for studying visually-coupled bimanual coordination in Chapter 3; and the Cube and Hi5 for studying haptically-coupled bimanual coordination in Chapter 4 and Chapter 5, respectively.

¹ One of the studies in this thesis involves healthy adults (age 18 - 30 years)

2.1 DEVICES

Two sensorised devices and one robotic interface were used in this thesis, as displayed in Figure 2.1. They were previously developed within the Human Robotics Group of Imperial College London. As a part of work within this thesis, some changes to the design, hardware and software were performed in order to fit the study purpose and the target population. These devices, as well as their customised software interfaces, were specifically programmed to institute visual and mechanical (i.e. haptic) coupling to the users. They were also programmed to modulate the properties of the coupling, such as the strength and the congruence of the physical connection between the two hands.

2.1.1 The GripAble: a compliant handgrip device

The *GripAble* is a digital handgrip device that allows patient-led therapy and objective assessment of the upper limb, designed by Mace *et al.* (2017b). It comprises a force-sensing mechanism which enables the handgrip to deform elastically when squeezed. The grip force data is measured using a force transducer (CZL635, Phidget Inc., linear range 0 - 49 N, rated output 1.0 ± 0.15 mV/V) embedded within the device. This force data is sent in real-time over Bluetooth, to control specially designed game-based rehabilitation tasks. In this thesis, the GripAble and the Balloon Buddy game (Mace *et al.*, 2017a) were used for investigating visually-coupled bimanual coordination, as reported in Chapter 3.

The *size* and the *design* of the GripAble were modified to ensure that the device is suitable for TD and USCP children between the age of 5 years to 18 years. Based on the anthropometric data of 5-year-old children in the UK (Figure 2.2), the average hand length, measured

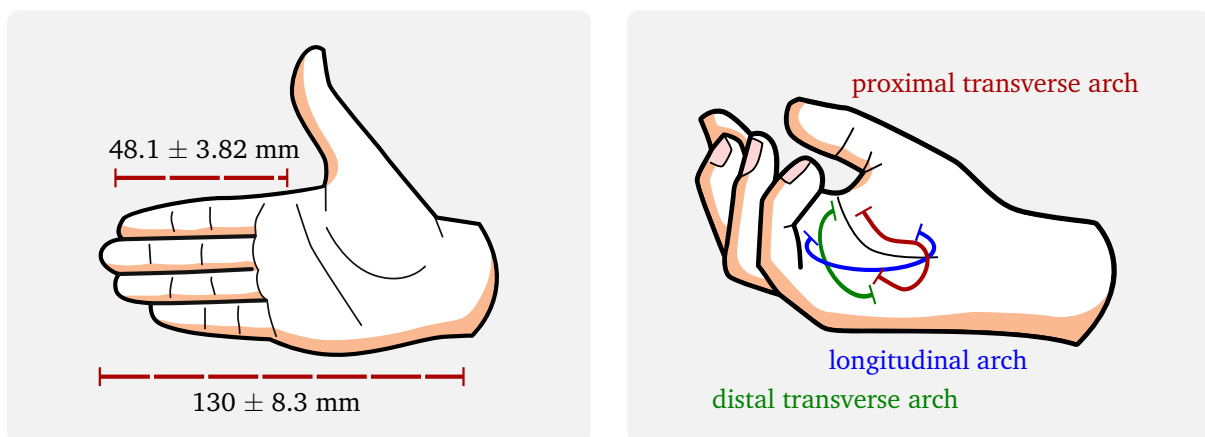


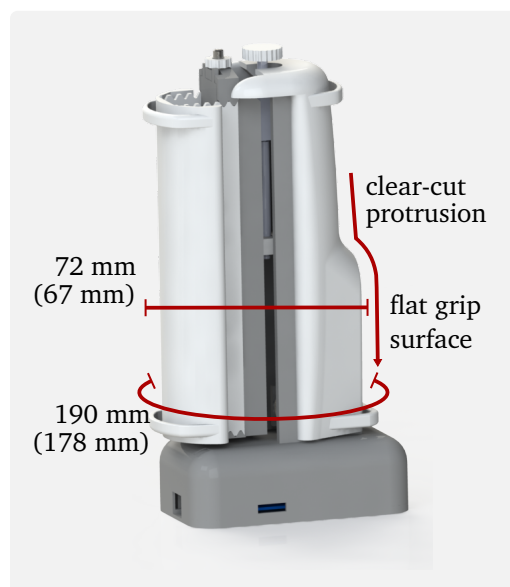
Figure 2.2 | **The anthropometry and the hand arches of 5-year-old children.** Shown are the anthropometric data of the hand length, measured from wrist crease to middle fingertip, and the index finger length (Porter, 2000).

from wrist crease to middle fingertip is 130 ± 8.3 mm and the length of the index finger is 48.1 ± 3.82 mm (Porter, 2000). The original size of the GripAble was 190 mm in circumference and 72 mm in width from front to back, which was judged to be too big for the youngest target age group of 5 years.

Besides the size, the design of the GripAble was modified to improve its ergonomics. As visualised in Figure 2.3, the clear-cut flat-surfaced protrusion in the outer body of the original design did not conform to the transverse and longitudinal arches of the hand (see Figure 2.2). Furthermore, the protrusion could cause significant discomfort to users, as the edges might compress the median nerve, as well as the flexor and adductor pollicis brevis muscles, especially under higher grip forces.

Therefore, the GripAble was redesigned by replacing the force transducer, which was 12.7 mm x 55.25 mm x 12.7 mm in size, with a significantly smaller transducer (TAL230A, HT Sensor Technology, linear range 0 - 98 N, rated output 1.1 ± 0.15 mV/V), of size 8 mm x 40 mm x 2 mm. This change allowed for the circumference and the front-to-back width of the device to be reduced by 20 mm and 8 mm, respectively. The change also allowed for the shape of the outer body to be smoothed-out and curved, in a way that the GripAble sits comfortably on the arches of the hand when grasped (Figure 2.3). All modifications were performed in SolidWorks® (Dassault Systèmes, USA).

ORIGINAL DESIGN



MODIFIED DESIGN

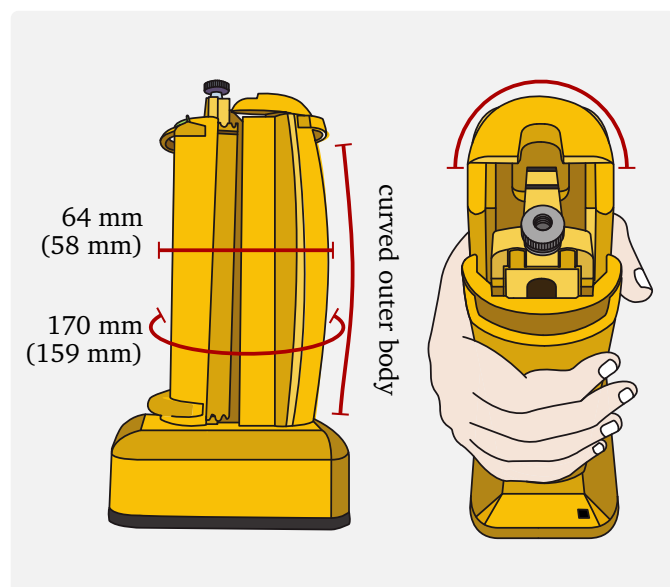


Figure 2.3 | The GripAble: a digital handgrip device. Shown are the original and modified GripAble design. The measurements of the circumference and the front-to-back width are shown in: when grip is fully released (when grasped to the maximum range). This device was used for measuring visually-coupled bimanual coordination in Chapter 3.

2.1.2 The Cube: an instrumented toy

The *Cube* is a bespoke instrumented device of dimension 100 mm x 100 mm x 100 mm and weight 530 g (Figure 2.4A). It was used as a measurement tool for measuring upper limb coordination during a haptically coupled bimanual task in Chapter 4. The Cube's size was selected to make it impossible for children subjects to lift it with one hand alone (see Figure 2.4B for the relative size of the hands of a child aged 6.9 y, compared to the dimension of the Cube).

A significant change in the electronics of the Cube was performed to improve its functionality and ease of operation. The Cube was initially designed with a force-sensing resistor (FSR) sensor (Square FSR, Interlink Electronics, linear range 0 - 98 N) on each face to measure the force applied on each side of the Cube, as well as its interaction with the ground or table. The main problem with using an FSR was that this type of force sensor typically produces *hysteresis prone, non-repeatable* readings, due to its highly voltage-dependent electrical resistance ($\pm 15\%$ to $\pm 25\%$ repeatability), which was deemed unsuitable for precise measurement required by this thesis. An additional issue with using an FSR was that its active sensing area was only 45mm x 45 mm, which was approximately half the size of the Cube faces. As visualised in Figure 2.5, the small sensing area of the FSR created a 'dead zone' around the edges of Cube, which was unable to measure force input — therefore requiring a more accurate application of forces relative to the Cube's faces.

All six FSRs were replaced with strain gauge type force sensors (TAL107E, HT Sensor Technology, linear range 0 - 10 kg, rated output 1.0 ± 0.2 mV/V), which can provide more linear, accurate, and repeatable readings. Figure 2.6A shows the output voltage from a calibration test conducted on all six faces of the Cube, tested with 200 gm, 400 gm, 600 gm, 800 gm and

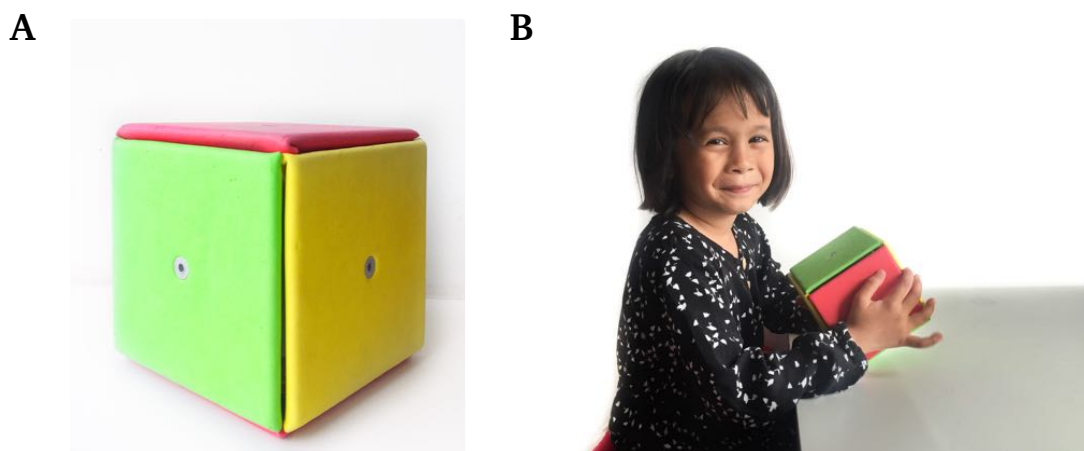


Figure 2.4 | The Cube: an instrumented toy. A. Shown is the Cube, an instrumented device for measuring hand coordination during haptically-coupled bimanual tasks in Chapter 4. B. Shown is the relative size of a child's hands aged 6.9 y, to the dimension of the cube

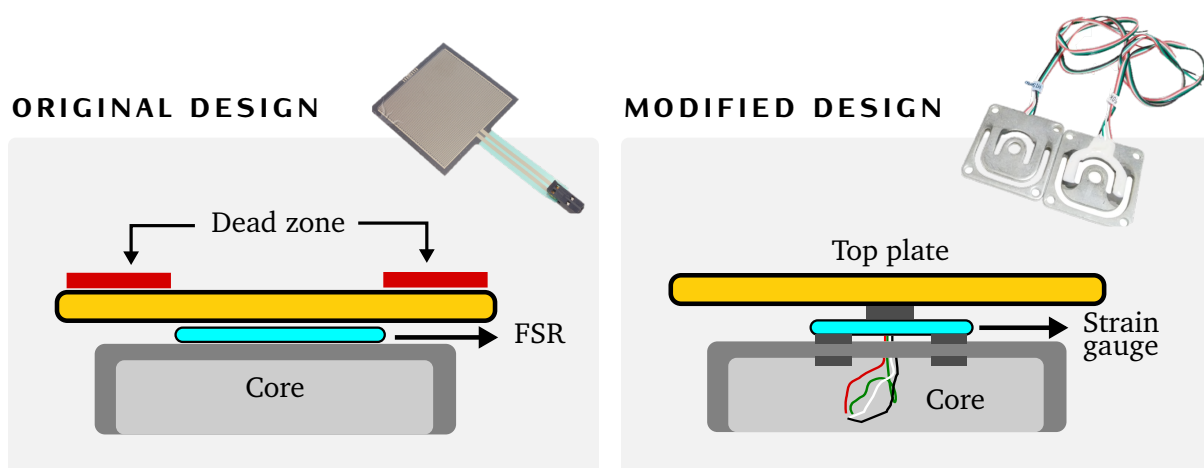


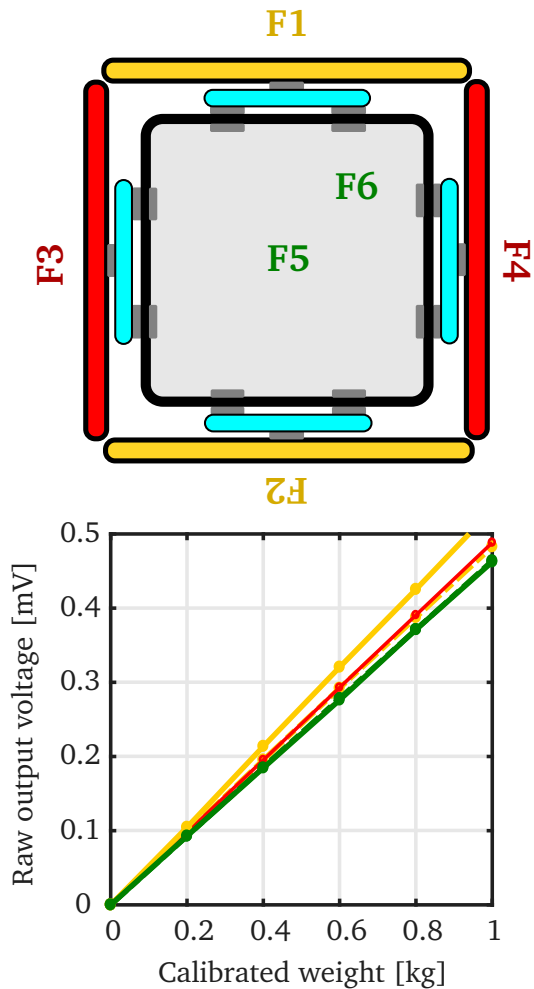
Figure 2.5 | The original and the modified designs of the Cube. Shown is the dead zone created in the original design of the Cube, in which the active sensing area of the FSR (shown at the top right of the left figure) was 55% smaller than the area of the Cube's faces. The modified design used strain gauges to support force measurement at any points on the Cube's faces.

1000 gm calibration weights. Five measurements were recorded for each calibration weight. The results show that the strain gauges produced very precise readings, as the relative error of the 5 measurements were all less than $< 0.1\%$ of the mean value. The linear behaviour of the strain gauges was calculated and the results show that the slope and the y-intercept remained constant throughout the 5 readings for all strain gauges. Furthermore, an eccentricity test was performed on 9 different points of one of the Cube's faces, using a 1000 gm calibration weight (Figure 2.6B). The results demonstrate that the measurement error between the centre point and the points around the edges remained relatively low, i.e. $\approx \pm 5\%$ error.

All data from the sensors were acquired using a microprocessor board Arduino Fio (ATmega328V microcontroller, operating voltage 3.3 V, supply voltage 5 V, 8 analog pins). Arduino Fio has a 10-bit analog-to-digital (ADC), which means that the resolution of the analog input pins are $5 \text{ V} / 2^{10} \approx 4.9 \text{ mV}$. Since the chosen strain gauge provides an output voltage of 0.1 mV/V/kg , theoretically, the board cannot recognise any variations that are less than 49 kg — which is beyond the strain gauge's capacity — without an appropriate amplification and filtering. Therefore, a rail-to-rail instrumentation amplifier (INA326, Texas Instrument), programmed with 1000 gain and 17 Hz cut-off frequency using an RC filter, was incorporated to amplify the strain gauge's output voltage from 0.5 mV/5 V/kg to 0.5 V/5 V/kg .

To estimate the Cube's absolute orientation and linear translation, a 9 degree of freedom Bosch BNO055 Inertial Measurement Unit (IMU) was attached inside the Cube's core. Data from the force sensors and the IMU were recorded wirelessly over Bluetooth at 60 Hz and 10-bit resolution. A custom data collection program running on an Android tablet was created in the Unity game engine (Unity Technologies, USA).

A. STRAIN GAUGE CALIBRATION



B. ECCENTRICITY TEST

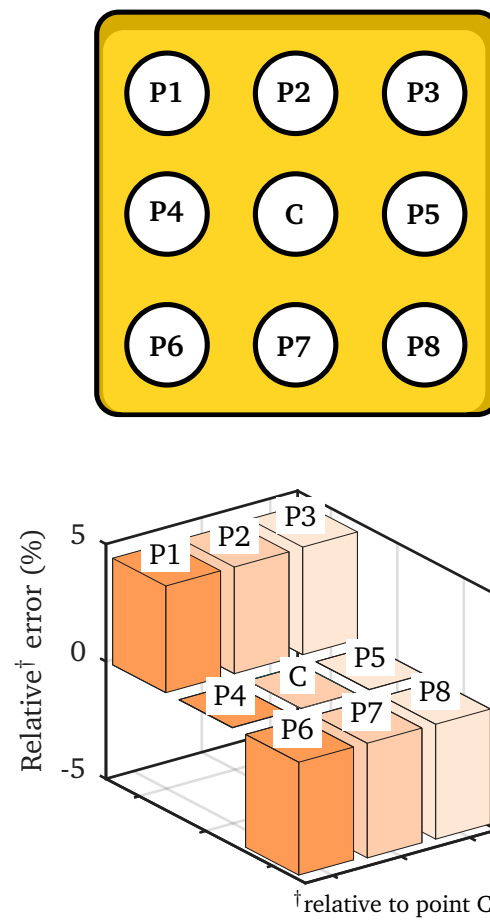


Figure 2.6 | The Cube calibration. Shown are **A.** The results from the strain gauge calibration carried out on all 6 faces of the Cube, tested at 200 gm, 400 gm, 600 gm, 800 gm, and 1000 gm calibration weights for 5 trials. The offsets were removed from the raw output voltages. **B.** The results from an eccentricity test that was conducted on 9 different points on one of the faces of the Cube, using a 1000 gm calibration weight, for 5 trials.

2.1.3 The Hi5: a dual-wrist robotic interface

The *Hi5* is a dual-wrist robotic interface that allows for systematic study of human's coordinated behaviours in position, torque and muscle activity during bimanual operation (Figure 2.7; Melendez-Calderon *et al.*, 2011), or when interacting with another human subject (Takagi *et al.*, 2018). This robotic interface allows the experimenter to provide computer-controlled torque onto one/both wrist joints through the motors embedded within the system. In this thesis, the Hi5 was programmed to modulate the stiffness of connection between the two hands, in an experiment reported in Chapter 5.

The Hi5 records the wrist flexion/extension angle and the torque applied by the wrist against the torque motor, at a 100 Hz sampling frequency. The instructions of the task, as well as subject-controlled cursor positions (corresponding to the movement of the wrists), are rendered at 66 Hz and displayed on a 23-inch screen positioned at eye level.

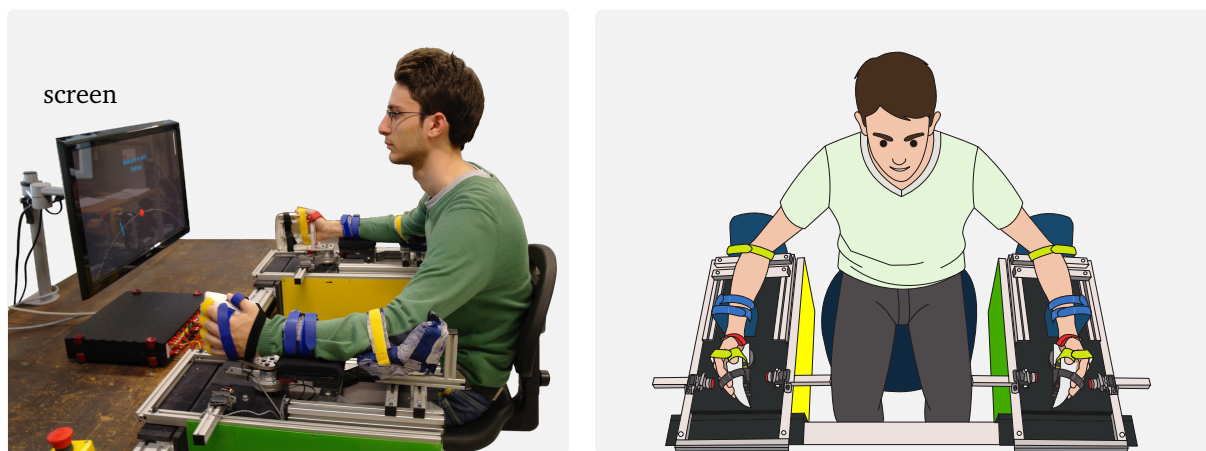


Figure 2.7 | The Hi5: a dual-wrist robotic interface. The Hi5 is used for measuring the influence of the connection stiffness between the two hands on bimanual coordination, in Chapter 5.

2.2 COORDINATION METRICS

Data analysis in this thesis involved an extensive quantification of upper limb sensorimotor coordination in TD and USCP children, as well as healthy adults. A significant part of this quantification was performed by analysing the synergies between two interdependent variables of interest, for example, the development of left and right grasp forces (Chapter 3), and the grasp-load synergy (Chapter 4). This analysis is motivated by previous studies by Johansson & Westling (1987) and Forssberg *et al.* (1991), who observed the slow development of sensorimotor coordination from infancy to adulthood using the analysis of grip-lift synergy, as previously discussed in Chapter 1. In these studies, the grip-lift synergy was quantified using the R^2 metric obtained from an ordinary least square regression analysis between the two variables, grip force and load force. This metric, which is also known as ‘linearity’, has been proven efficient and sensitive at quantifying one’s sensorimotor coordination, and has since inspired many researchers to adapt this computation method in their research.

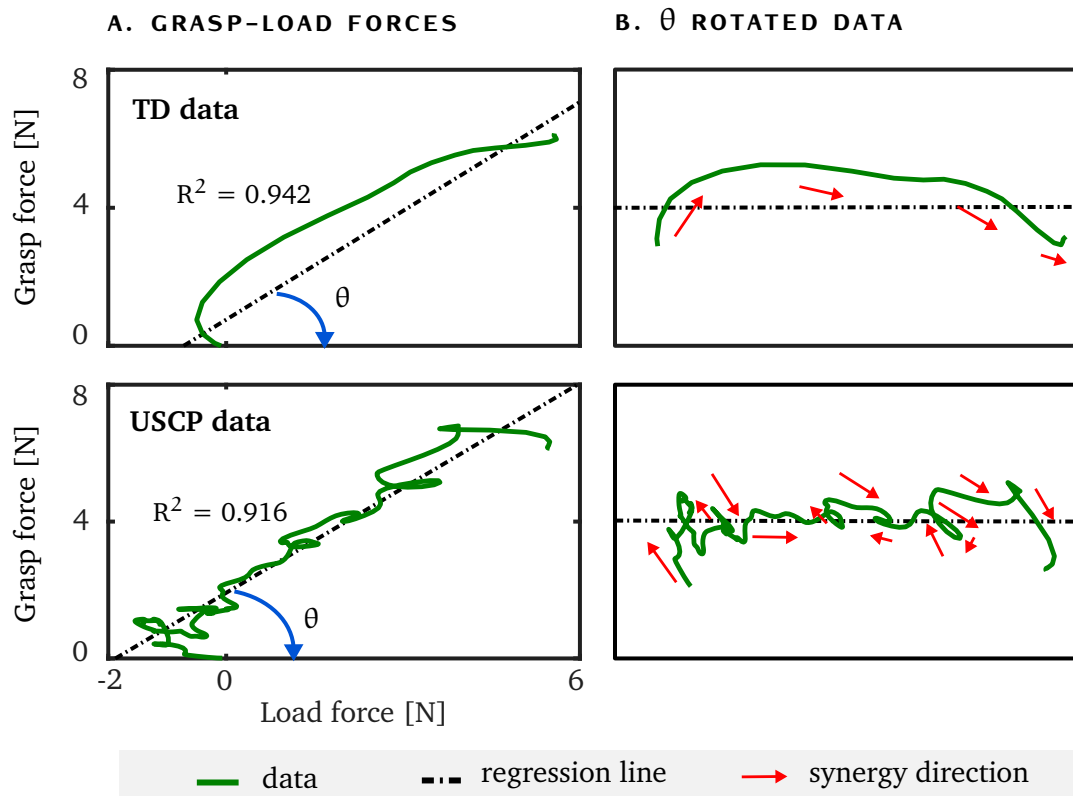


Figure 2.8 | The limitation of R^2 value (linearity) for measuring synergies between two variables of interest. Shown are **A.** the grasp force vs load force data of one TD (top) and one USCP (bottom) subjects during a simple lifting task, and **B.** the synergy directions in which the grasp and the load forces evolve. Although both subjects exhibit almost similar R^2 values, it is visible that the performance by USCP subject is more ‘uncoordinated’ than TD, where the development of grasp force and load forces with respect to their regression line are highly non-monotonic.

Despite its extensive use, this linearity metric has a major limitation, where it does not consider the temporal evolution in which the grasp force and load force develop, as illustrated in Figure 2.8. The figure shows the examples of grip force plotted against the load force data from a TD subject and a USCP subject during a simple lifting task, as carried out in Chapter 4. An ordinary least square regression analysis with load force as the predictor variable and grasp force as the dependent variable demonstrated that TD and USCP subject exhibit virtually similar R^2 values, which are 0.942 and 0.916 respectively. However, it can be observed from the plots that the grip-lift synergy of USCP subject is more ‘uncoordinated’ than that of TD, as the grasp and load force development of the USCP subject does not evolve monotonically with respect to its regression line, unlike the TD’s pattern. The observed non-monotonic development of grip and load forces could potentially characterise some underlying sensorimotor impairments that are unable to be distinguished using R^2 alone.

Due to its prevalence, the linearity metric was adapted in this thesis for measuring coordination synergies between two time-related variables of interest. However, considering its limitation, a new metric — *monotonicity* — was therefore developed by the author of this thesis, to provide a more sensitive method for quantifying the synergies between the two variables. Monotonicity describes the quality related to the continuity or non-intermittency of the two variables of interest with respect to their regression line and is best used as a complementary tool to the linearity metric, which measures the error between the predicted value and the actual value from the linear relationship.

Before implementing the metrics, a linear model that describes the synergy between two variables $\mathbf{V}^{(1)}$ and $\mathbf{V}^{(2)}$, must first be defined. Because it is assumed that these two variables are interdependent, the model should account for errors in both variables. As such, ordinary linear regression cannot be used in this scenario, as it only considers the errors from one of the variables (i.e. the dependent variable). Therefore, Deming regression, which is a type of total least square regression that considers the errors in observations from all variables, is thus chosen to describe the linear relationship between the two variables.

Using a series of N paired measurements $\{(\mathbf{V}_i^{(1)}, \mathbf{V}_i^{(2)}), i = 1, \dots, N\}$, the relationship between the variables $\mathbf{V}^{(1)}$ and $\mathbf{V}^{(2)}$ is estimated by a linear equation in the form

$$\hat{\mathbf{V}}_i^{(2)} = \alpha + \beta \hat{\mathbf{V}}_i^{(1)} \quad (2.1)$$

where α and β are the intercept and the slope of the relationship, respectively, and $\hat{\mathbf{V}}^{(1)}$ and $\hat{\mathbf{V}}^{(2)}$ are the estimates of $\mathbf{V}_i^{(1)}$ and $\mathbf{V}_i^{(2)}$ at time i -th, respectively. The least-squares approach of Deming regression minimises the sum of squares

$$\mathbf{s} = \sum_{i=1}^N \left[\left(\mathbf{V}_i^{(1)} - \hat{\mathbf{V}}_i^{(1)} \right)^2 + \lambda \left(\mathbf{V}_i^{(2)} - \hat{\mathbf{V}}_i^{(2)} \right)^2 \right] \quad (2.2)$$

where λ is the constant ratio of the two error variances of $\mathbf{V}^{(1)}$ and $\mathbf{V}^{(2)}$, which is assumed to be 1. The intercept α and the slope β estimates are computed by setting $\frac{d\mathbf{S}}{d\alpha}$ and $\frac{d\mathbf{S}}{d\beta}$ equal to zero, to yield

$$\alpha = \bar{\mathbf{V}}^{(1)} - \beta \bar{\mathbf{V}}^{(2)}, \quad \beta = \frac{s^{(2)} - \lambda s^{(1)} + \sqrt{(s^{(2)} - \lambda s^{(1)})^2 + 4\lambda s^{(12)}}}{2s^{(12)}} \quad (2.3)$$

with

$$s^{(1)} = \sum_{i=1}^N \left(\mathbf{V}_i^{(1)} - \bar{\mathbf{V}}^{(1)} \right)^2 \quad (2.4)$$

$$s^{(2)} = \sum_{i=1}^N \left(\mathbf{V}_i^{(2)} - \bar{\mathbf{V}}^{(2)} \right)^2 \quad (2.5)$$

$$s^{(12)} = \sum_{i=1}^N \left(\mathbf{V}_i^{(1)} - \bar{\mathbf{V}}^{(1)} \right) \left(\mathbf{V}_i^{(2)} - \bar{\mathbf{V}}^{(2)} \right) \quad (2.6)$$

and $\bar{\mathbf{V}}^{(1)}$ and $\bar{\mathbf{V}}^{(2)}$ are the means of the $\mathbf{V}_i^{(1)}$ and $\mathbf{V}_i^{(2)}$ values respectively. The full derivation of Deming regression can be found in Jensen (2007).

LINEARITY The linearity of the two variables of interest, $\gamma_{(1,2)}$ is calculated from the standard error of Eqn. (2.1), in the form

$$\gamma_{(1,2)} = -\frac{1}{N-2} \sqrt{\sum_{i=1}^N \left(\mathbf{V}_i^{(1)} - \hat{\mathbf{V}}_i^{(1)} \right)^2 + \left(\mathbf{V}_i^{(2)} - \hat{\mathbf{V}}_i^{(2)} \right)^2} = \gamma_{(2,1)} \quad (2.7)$$

where $\mathbf{V}_i^{(1)}$ and $\hat{\mathbf{V}}_i^{(1)}$ are the real and estimated value of $\mathbf{V}^{(1)}$, while $\mathbf{V}_i^{(2)}$ and $\hat{\mathbf{V}}_i^{(2)}$ are the real and estimated value of $\mathbf{V}^{(2)}$, at time i -th.

MONOTONICITY To calculate the monotonicity of a relationship between the two variables, the vector that defines the relationship are computed from Eqn. (2.1), which is in the direction of the principal axis ρ (i.e. regression line; Figure 2.9B). The monotonicity of the synergy between the two variables $\mu_{(1,2)}$ is then calculated as

$$\mu_{(1,2)} = \left| \frac{1}{N-1} \sum_{i=1}^{N-1} d\mathbf{I}_i \right| = \mu_{(2,1)}, \quad d\mathbf{I}_i = \begin{cases} 1 & \text{if } \tilde{\mathbf{V}}_{i+1}^{(1)} - \tilde{\mathbf{V}}_i^{(1)} > 0 \text{ (monotonic)} \\ -1 & \text{otherwise (non-monotonic)} \end{cases} \quad (2.8)$$

where $\tilde{\mathbf{V}}^{(1)}$ is the rotation of $\mathbf{V}^{(1)}$ matrix based on the angle θ , which is calculated from the slope β from Eqn. (2.1), as

$$\begin{bmatrix} \tilde{\mathbf{V}}^{(2)} \\ \tilde{\mathbf{V}}^{(1)} \end{bmatrix} = \mathbf{R}(\theta) \cdot \begin{bmatrix} \mathbf{V}^{(2)} \\ \mathbf{V}^{(1)} \end{bmatrix}, \quad \mathbf{R}(\theta) = \begin{bmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{bmatrix}, \quad \theta = \tan^{-1}(\beta) \quad (2.9)$$

The monotocity score ranges from 0 for an entirely non-monotonic relationship, to 1 for a perfectly monotonic relationship.

The difference between linearity and monotonicity is illustrated in Figure 2.9A. Eqn. (2.9) is explained geometrically in Figure 2.9B. All metrics were developed in MATLAB® (The Math-Works, USA).

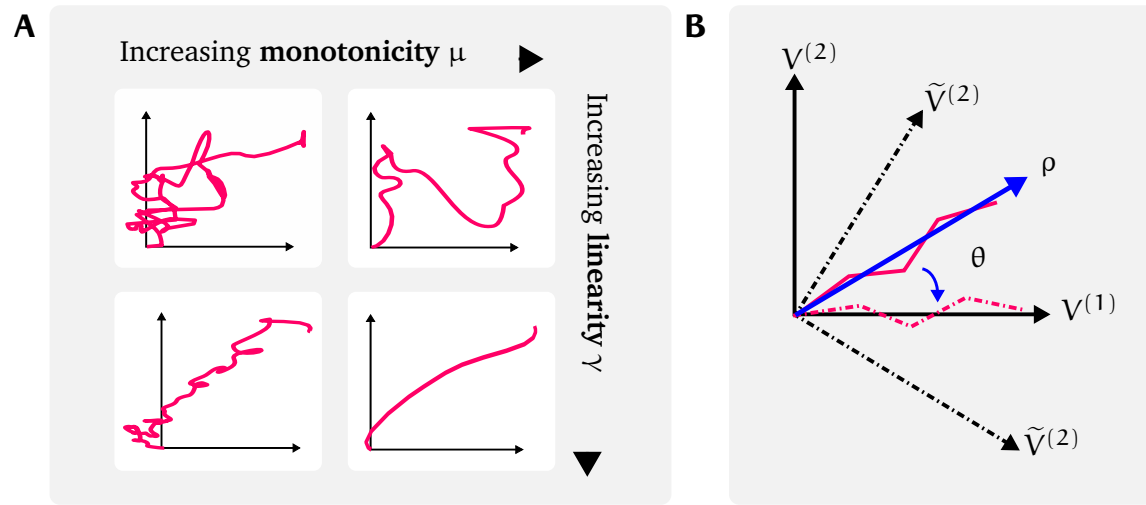


Figure 2.9 | The measure of linearity and monotonicity. Shown are **A.** the illustration of monotonicity and linearity concepts, and **B.** the illustration of the two-dimensional rotation of the $V^{(1)}$ and $V^{(2)}$ relationship in the direction of the principal axis ρ (i.e. regression line), at θ angle.

3 | VISUALLY-COUPLED BIMANUAL COORDINATION

This chapter begins the series of investigations looking into bimanual coordination during physically-coupled tasks, by exploring the potential of *visual feedback* in facilitating bimanual movements in TD children, children with USCP and healthy adults. Certainly, one of the most important receptors for supplying information about the movement of objects we are interacting with, as well as the movement of our limbs during that interaction, is the *eye*. Volumes of literature have established the importance of visual feedback in guiding the movements of our limbs. For instance, if a person closes their eyes while reaching for an object, their performance would severely deteriorate, where the grasp aperture will get wider, the general movement will slow down, and the endpoint will be less accurate (Wing *et al.*, 1986).

Likewise, visual feedback is crucial for coordinating bimanual movements. Franz & McCormick (2010) demonstrated that, when moving two objects that are visually and perceptually unified, the timing and precision of a movement improved relative to an equivalent non-unified task. The improvement was similar to that found during a spatially unified bimanual task (Franz *et al.*, 2001), and was hypothesised to be due to “integrating separate task components into a single representation (a concept) may be functionally equivalent to maintaining one thought, or cognitive set, at a time” (Franz *et al.*, 2001, p. 111). Potentially, this ‘shared’ visual connection could have reduced the cognitive load required for planning and anticipation, thus ‘simplifying’ the strategy needed to synchronise the movement of both hands.

However, the similar potential has never been exploited in TD and USCP children. Given the cognitive impairment sometimes observed in children with USCP (Rosenbaum *et al.*, 2007), the drawn attention to the shared object in a visually-coupled bimanual task could reduce cognitive burden and interference associated with performing ‘two tasks at once’ in an uncoupled bimanual task, thus allowing these children to process and plan their movement faster. Therefore, this chapter intends to understand motor behaviours during this task setup, with the predominant focus being on the understanding of how visual feedback in-

fluences bimanual grip control/scaling, and how it can facilitate bimanual coordination in children with impaired sensorimotor and cognitive functions like USCP.

Before undertaking any sensorimotor studies on children with USCP, it is imperative to first understand how motor strategies develop and manifest in individuals with typical development, and compare how neurological and sensorimotor impairments alter these strategies. Therefore, the first experiment in this chapter investigates the typical development of unimanual and visually-coupled bimanual grasp coordination from childhood to adulthood. Data from these children and adults will serve as the basis to properly understand impaired unimanual and bimanual coordination in children with USCP, as well as how visual feedback can facilitate and enhance the synergistic movement of both hands.

Using the knowledge gained from this experiment, this chapter then proceeds to investigate the grip coordination of TD and USCP children when one of the hands is randomly perturbed. The perturbation is incorporated by changing the input force to control output gain, thus affecting the expected visuomotor mapping. The particular interests of this experiment are on (1) how these children alter their grip in response to these perturbations, and (2) whether they can recover to their baseline strategy on the subsequent unperturbed trial. While some studies have investigated children with USCP's responses to perturbation during bimanual control, most of these have only exploited a change in the physical properties of an object, such as weight (Gordon & Duff, 1999; Forssberg *et al.*, 1992) and surface texture (Gordon & Duff, 1999; Eliasson *et al.*, 1995). In contrast, no study has explored how these children respond to perturbation when the grip demanded on each hand is incongruent. Understanding these responses will help to further understand the emergence of anticipatory control in children. In children with USCP, impaired sensorimotor integration and poor internal representation are amongst the major contributing factors for their impaired anticipatory control (Gordon *et al.*, 2006a; Eliasson *et al.*, 1992). While these two factors may not be distinguishable in this experiment, the difference in control strategy from the non-affected and affected hands may give an idea of how sensorimotor deficits influence bimanual anticipation and synergy.

Both experiments were carried out using the *Bimanual Balloon Buddy* game. This game is a modified version of the Balloon Buddy game (Mace *et al.*, 2017a), which is a novel game-based paradigm developed for investigating normal and pathological behaviours of unimanual and visually-coupled bimanual coordination, as well as human-human interaction. Here, subjects control one or two visually-coupled game objects by controlling the amount of grip force onto a digital handgrip device, the GripAble, which was described in Chapter 2.1.1.

3.1 BIMANUAL BALLOON BUDDIES: A VISUALLY-COUPLED GAME-BASED PARADIGM

The first study in this chapter aims to investigate the coordination of grip force generation and scaling during a unimanual task in children with TD and USCP, and compare how their grip coordination is altered when performing a visually-coupled bimanual task. However, designing a study protocol for measuring the grip coordination amongst children, especially in a virtual environment, is challenging. Besides making sure the task fits the study's objectives, it should also be *comprehensible*, especially for younger or cognitively delayed children with USCP. The task should also incorporate an *adequate number of repetitions* to capture true sensorimotor ability. As such, a small number of trials might not be robust enough to measure a child's full potential. However, a task that is too long may yield meaningless data due to loss of interest or tiredness.

A child's interest in the task is critical to ensure the child remains fully engaged throughout the experiment. Erhardt (1992) suggested that, when planning an intervention to practice eye-hand coordination, the therapist must consider the child's cognitive development and the child's natural desire to play, because these factors are the impetus for "purposeful, goal-directed, eye-hand coordination behaviours" (p. 23). Here, three key factors were considered before finalising the protocol for the experiment:

GAMIFIED an important factor to consider, as a gamified task can excite children for its attractiveness, motivation, and engagement, and can stimulate reward-related dopaminergic systems in the brain that facilitates learning (Janssen *et al.*, 2017). The real-time performance feedback and rewards within the game (e.g. in the form of points collected) can motivate children to achieve task goals and maintain focus throughout the task.

INTUITIVE a game with clear strategy and graphics allows children to understand the tasks faster while minimising distraction.

SHORT a shorter game can increase the probability of subjects to remain engaged throughout the task, and decrease the chance of tiredness/muscle fatigue, especially amongst young children.

Considering all of these factors, a novel game-based paradigm — Bimanual Balloon Buddy game — was developed for investigating the unimanual and bimanual coordination amongst children and adults, as well as between human partners. The game is a simplified version of Balloon Buddies, which was originally developed by Mace *et al.* (2017a). For this study, the game was redesigned to fit the aim and the target group of the experiments. The development and modification of the game were performed in the Unity3D game engine (Unity Technologies, USA).

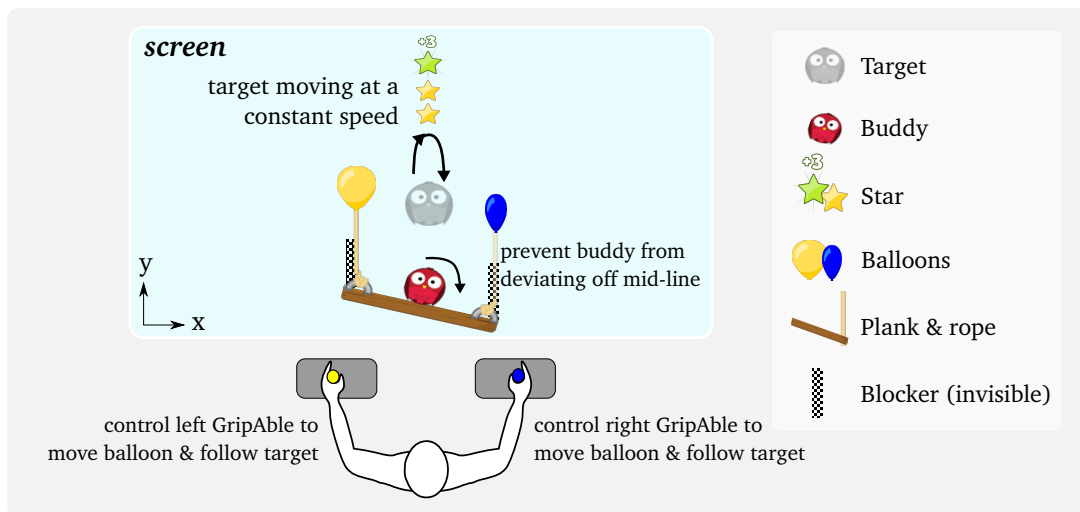
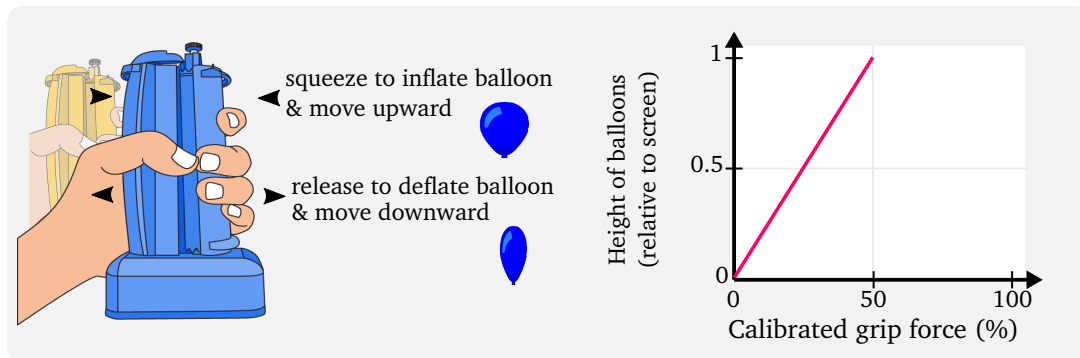
GAME**CONTROL MECHANISM**

Figure 3.1 | The Bimanual Balloon Buddies game interface. Shown are the game setup, visuals, mechanism and controls. A balloon is controlled by squeezing a GripAble to inflate and thus move the balloon upward, while releasing the grip deflates thus moving the balloon downward. The invisible blockers on both sides of the plank are added to prevent the buddy from falling, so as to avoid frustration from repeated failures, especially amongst children.

Figure 3.1 shows the environment and the mechanism for controlling the game. The primary goal of the game is to vary the inflation level of the balloons so that the height of the 'buddy' matches the height of a moving target behind. A secondary goal is to collect all the stars, thus requiring the player to keep the buddy in the middle of the plank. The inflation level (height) of the balloon is controlled by modulating the amount of grip force onto the GripAble (see Chapter 2.1.1 for the description of the GripAble). The player needs to squeeze the GripAble to move the balloon upward and release the grip to move the balloon downward. Before playing, the software is calibrated based on the minimum grip force (when the hand is resting) and 50% of the maximum power-grip ability of each hand. These force values are then mapped to control the inflation level of the balloons, on a 0 - 1 scale, such that 0: moves

a balloon to the bottom and 1: to the top of the screen. As illustrated in Figure 3.2, the game comprises three different control modes:

UNIMANUAL PREFERRED the preferred side (the dominant side for TD or the non-affected side for USCP) controls the balloon that corresponds to its side while the other is controlled by a computer. The computer-controlled balloon moves at the same speed as the target.

UNIMANUAL NON-PREFERRED the non-preferred side controls the balloon that corresponds to its side while the other is controlled by a computer. The computer-controlled balloon moves at the same speed as the target.

BIMANUAL both hands control the corresponding balloons simultaneously.

At the end of every trial, the game provides three scores related to the player's *performance*:

STABILITY reflects how well the plank is held horizontally, measured as the percentage of frames where the vertical difference between the two ends of the plank is less than a fixed threshold (<20% of buddy's diameter)

ACCURACY is computed as the percentage of frames in which the centre of the buddy lies within a vertical margin of the target's trajectory (i.e. <50% of the target's diameter).

NUMBER OF STARS is a gross indicator of a player's ability to follow the target and complete a trial. A star is 'collected' when any part of the buddy's body collides with any part of a star positioned towards the top or the bottom of the screen. The number of stars is presented to subjects in real-time, as a cumulative score in the top of the screen (green star: 3 points, yellow star: 1 point; maximum total points: 10).

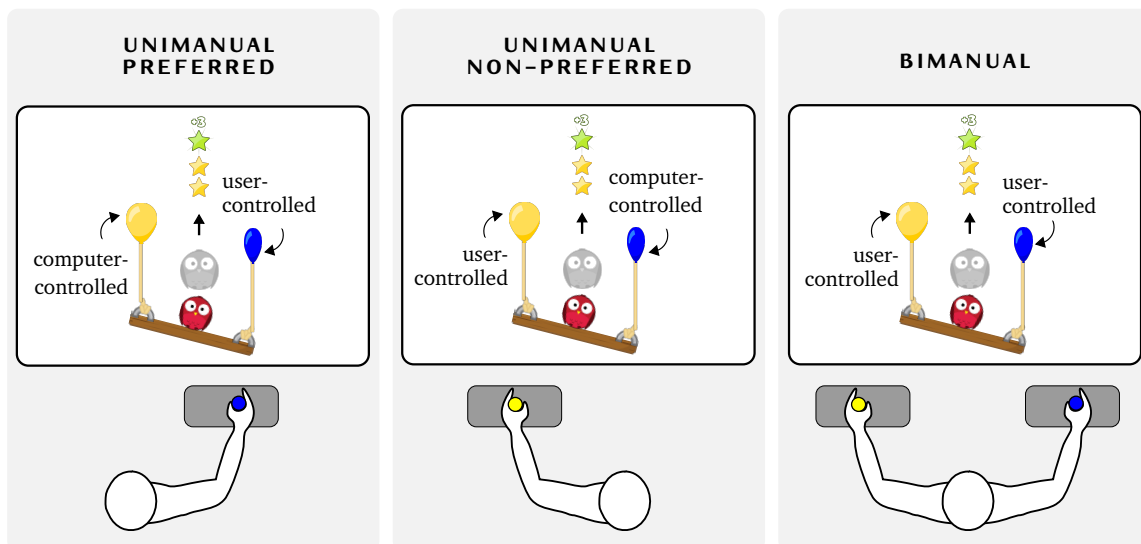


Figure 3.2 | Three different control modes of Bimanual Balloon Buddies game. During the preferred and non-preferred unimanual modes, subjects control the balloon on the corresponding side, whereas the other balloon is controlled by a computer. This is an example of the game protocol for individuals with right-hand dominant/right-hand non-affected.

3.2 VALIDATING GAME-BASED EXPERIMENT FOR CHILDREN

In order to test the Bimanual Balloon Buddies game, a preliminary experiment was conducted on 7 TD children (mean age 8.6 yrs, standard deviation 1.3 yrs; range 6 - 9.9 yrs; 4 M 3 F; 6 right-handed). Each subject played a total of 21 trials: 7 unimanual preferred, 7 unimanual non-preferred and 7 bimanual trials. When performed accurately, a single trial lasted approximately 25 seconds. A limit of 50 seconds was given for each trial. A 10-second rest was given between consecutive trials, as well as a 2-minute rest before proceeding to the next game mode. Before starting the experiment, subjects were also given an option to pause when needed. The experiment lasted 25-30 minutes from set-up to completion.

The primary aim of this experiment was to examine whether children are able to comprehend the Bimanual Balloon Buddies game. Therefore, each subject was only briefly explained the game's control strategy before starting the experiment. The secondary aim was to observe the children's engagement and persistence levels throughout the task. This information was vital for deciding the suitable duration of this game-based experiment. To record the subjects' engagement and persistence levels, two questions: "*Are you bored?*" and "*Are you tired?*", were verbally asked at the end of the 7th, 14th and 21st trial. The experiment was halted as soon as the subject reported 'bored' or 'tired' and expressed disinterest to continue the task. To quantitatively analyse the subjects' performance, both game-dependent stability and accuracy scores were recorded and analysed.

A quantitative analysis of the subjects' performance, as shown in Figure 3.3 demonstrated that subjects were generally able to comprehend the task, evidenced from the improvement or 'learning effect' observed between the first and the fifth trials of every control mode. Figure 3.4 illustrates the subjects' response to the two questions. All subjects remained engaged throughout the first 7 trials. After the 14th trial, 1 out of 7 subjects (the youngest subject, age 6) reported bored + tired. At the end of the 21st trial, 1 out of 6 remaining subjects reported bored + tired, whereas another 2 out of 6 subjects reported only bored with the task.

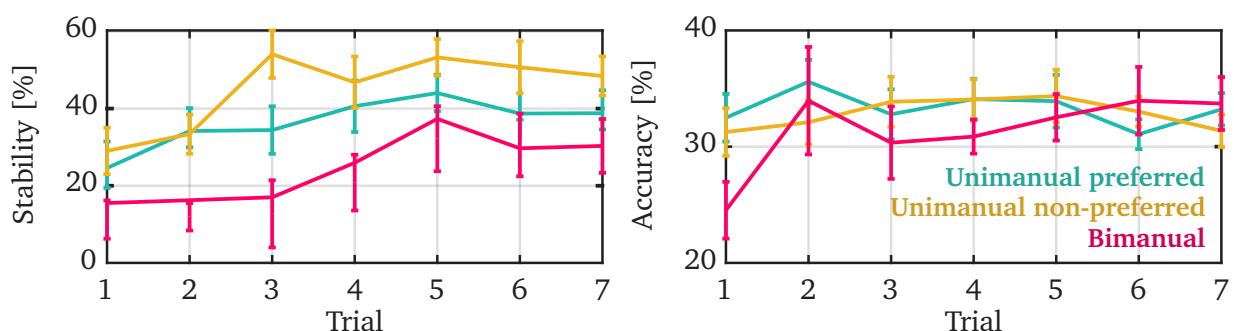


Figure 3.3 | **Preliminary stability and accuracy scores for 7 TD subjects.** Shown are the medians $\pm$ standard errors for each control mode, across 7 trials.

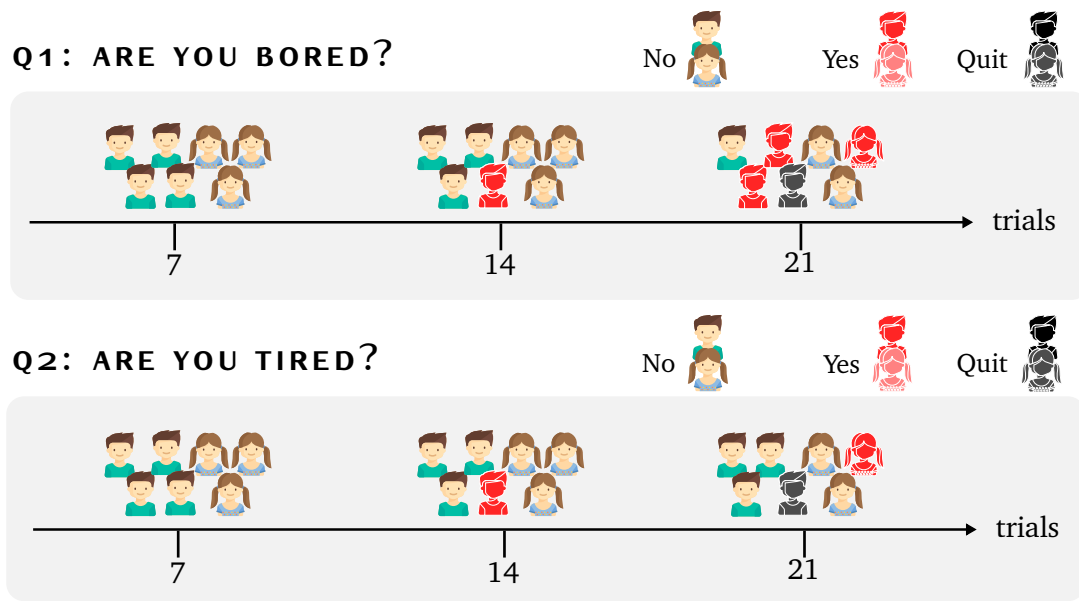


Figure 3.4 | **The engagement and persistence levels for 7 TD subjects.** Two questions — “are you bored?” and “are you tired?” — were asked at every 7th trial, in order to record subjects’ engagement and persistence levels, respectively.

Collectively, these preliminary results suggest that children were able to understand the game strategy after one or two trials. However, to maximise engagement throughout an experiment, the final protocol of the game should incorporate only ≤ 5 trials for each control mode, or up to a maximum of 15 trials of the Bimanual Balloon Buddies game. Rest should also be given in-between trials, as well as whenever needed. The decision of whether rest is needed is best determined by verbally asking the subjects if they require a break, especially when dealing with shy and quiet subjects.

3.3 UNIMANUAL AND BIMANUAL GRASPING TASK

32 TD children (mean age 8.68 yrs, standard deviation 2.06 yrs; range 4.52 - 11.98 yrs; 17 M 15 F; 28 right-handed), 7 children with USCP (mean age 10.84 yrs, standard deviation 2.81 yrs; range 7.54 - 15.04 yrs; see Table 3.1 for subjects with USCP' biographical information) and 24 healthy adults (14 M, 10 F; 23 right-handed, measured according to the Edinburgh Handedness test) were recruited in this first experiment. The inclusion criteria for TD subjects include no specific learning difficulties and the ability to play video games. For subjects with CP, criteria include diagnosed as 'unilateral spastic' according to the Surveillance of Cerebral Palsy in Europe (SCPE), with MACS level of I-III (refer to Appendix A for the description of MACS levels), no visual or musculoskeletal impairments and the ability to play video games. All subjects under 18 years old gave their verbal assent, and informed consent was obtained from the accompanying parent. All subjects above 18 gave their informed consent before the experiment. The experiment was approved by the Imperial College Research Ethics Committee (UK) for study on TD and healthy adult subjects, University of Sultan Zainal Abidin Human Research Ethics Committee (Malaysia) for TD subjects and National Health Group Domain Specific Review Board (Singapore) for subjects with USCP.

Table 3.1 | Descriptive information for the subjects with USCP for the visually-coupled bimanual experiment. Spasticity level was assessed using the Modified Ashworth Scale ranging from 0 to 4 (Bohannon & Smith, 1987). M, male; F, female.

Subject	Sex	Age (yrs)	Hemiparetic side	Spasticity (pronators)	Spasticity (wrist flexors)	MACS level
1	F	11.77	Right	1+	1+	2
2	F	7.54	Left	1+	1+	1
3	M	15.04	Right	3	3	1
4	F	9.60	Right	1	1	1
5	M	8.24	Left	2	1+	3
6	F	13.82	Right	2	2	2
7	F	9.86	Left	1+	1+	1

The experiment was conducted individually in a quiet room with minimal distractions. At least one parent or guardian accompanied subjects below 18. Each subject played a total of 15 trials of the Bimanual Balloon Buddy game, which constitutes 5 unimanual preferred, 5 unimanual non-preferred and 5 bimanual in a randomised block order. 10-second rest was given in between trials, as well as when requested by subjects. The experiment lasted approximately 20 minutes, including preparation time. The game data (i.e. time, game frame and x - and y -trajectories of the balloons, target and buddy), the game-dependent accuracy and stability scores and the grip-force signals from the GripAble were wirelessly recorded at 70 Hz through a custom data collection thread running within the game.

3.3.1 Data analysis

Figure 3.5 shows the example signal (the trajectories of balloons and target) from one TD and USCP subjects. To remove noise and spurious artefacts, the grip-force signals were forward-backwards filtered using a 4th order low-pass Butterworth filter with a 10 Hz cut-off frequency. Besides the game dependent performance measures (i.e. stability and accuracy), the unimanual and bimanual generation grip force was quantified in terms of linearity and monotonicity, which describes how well the object was controlled with reference to its temporal evolution (i.e. target's movement). To compute these scores, the linear relationship between two variables, the height (y— coordinates) of the buddy $\mathbf{H}^b$ and the height of the target $\mathbf{H}^t$, were computed, with $\mathbf{H}^t$ as the predictor variable and $\mathbf{H}^b$ as the dependent variable, in the form

$$\mathbf{H}^b = \alpha_1 + \beta_1 \mathbf{H}^t \quad (3.1)$$

where α_1 is the y-intercept and β_1 the linear slope, which were calculated using Eqn. (2.3) as described in Chapter 2.2. The monotonicity score μ_{bt} of the grip force synergy between these two variables was then computed using Eqn (2.8) (Chapter 2.2), which was calculated separately for upward (grip) and downward (release) movements. The final monotonicity score was obtained from the average of these two scores. Similarly, the linearity score γ_{bt} was computed from the summation between Eqn. (2.7) and 1.

The median value (out of 5 trials) of each variable was chosen as a representative measure to ensure the robustness of the data to outliers. Due to the relatively small sample sizes and non-Gaussian distributions of the variables of interest, four non-parametric statistical tests were used throughout this experiment for testing performance differences between the control modes:

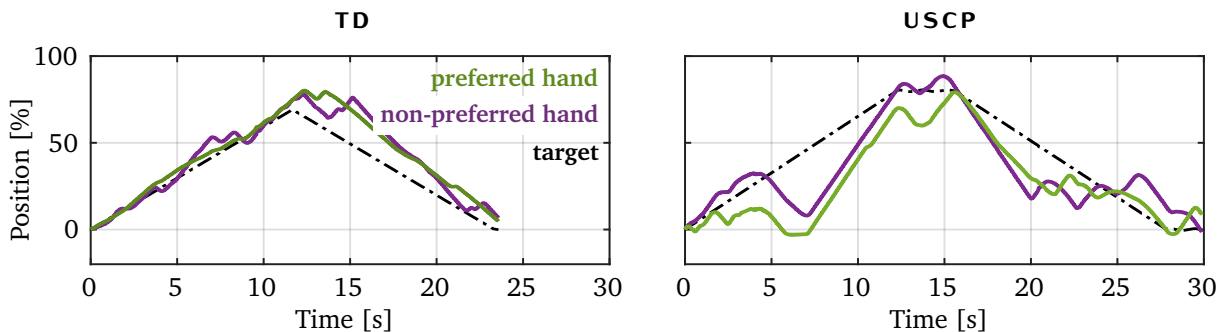


Figure 3.5 | Example signals during the unimanual vs. visually-coupled bimanual experiment from one TD and USCP subjects. Shown are data from one TD subject age 8.7 yrs and one USCP subject age 11.8 yrs during the bimanual mode. Both figures show the target's trajectory (dashed black line), as well as the balloons' trajectories of the preferred hand (green line) and the non-preferred hand (purple line).

FRIEDMAN TEST to test the overall effect of control modes on performance, followed by a post hoc multiple pairwise comparison test using Nemenyi's method, to analyse the statistical differences between all three pairs of control modes: (1) preferred vs. non-preferred, (2) preferred vs. bimanual and (3) non-preferred vs. bimanual.

KRUSKAL-WALLIS TEST to test the overall influence of age groups on performance, followed by post hoc Dunn-Sidák multiple pairwise comparison test to analyse the overall differences between (1) younger (age < 8 yrs; n = 8; mean age 5.84 ± 1.17 yrs) and older (age > 8 yrs; n = 24; mean age 9.63 ± 1.21 yrs) TD subjects, (2) TD and healthy adult, and (3) TD and USCP.

WILCOXON SIGNED-RANK TEST to analyse the difference in performance between two paired samples, e.g. between preferred and non-preferred hands during the bimanual control mode.

SPEARMAN'S CORRELATION COEFFICIENT TEST (ρ) to analyse the correlation between TD's performance and age, as well as between USCP's performance and MACS level.

To investigate the difference in the rate of change of scores, with respect to age, between every pair of control modes, the slope β_2 from an ordinary least square regression with age **A** as the predictor variable, and the scores **S** as the dependent variable, in the form

$$\mathbf{S} = \alpha_2 + \beta_2 \mathbf{A} \quad (3.2)$$

was bootstrapped 10,000 times. β_2 represents the rate of change of scores with respect to age and α_2 represents the y-intercept between the relationship. The significant difference between the slope β_2 of every pair of control modes was then calculated based on these bootstrap distributions. Similarly, the difference in the rate of change of scores between younger and older TD subjects was investigated by calculating and comparing the slope β_2 for each group. All statistical differences were calculated at 95% confidence level. Results are reported as median $\pm$ interquartile range. Most data in this chapter will be visualised in the form of *violin plots*. The interpretation of a violin plot is as illustrated in Figure 3.6.

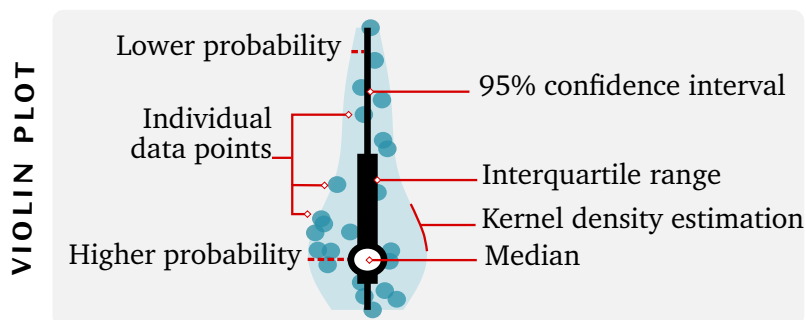


Figure 3.6 | The interpretation of a violin plot.

3.3.2 Results

Table 3.2 gives the median $\pm$ interquartile range scores of the five performance measures across all three control modes for all subject groups. For TD and healthy adult subjects, the dominant hand was considered as the preferred hand, whereas for subjects with USCP, the non-affected hand was considered as the preferred hand.

Table 3.2 | The performance of all subjects. Shown are the median $\pm$ interquartile range scores across the three game control modes (unimanual preferred, unimanual non-preferred or bimanual) during the unimanual vs. visually-coupled bimanual experiment.

Performance measure	Mode	Healthy adults (n = 24)	TD (n = 32)	USCP (n = 7)
Number of stars [#]	Preferred	10 $\pm$ 0	10 $\pm$ 0	10 $\pm$ 0
	Non-preferred	10 $\pm$ 0	10 $\pm$ 0	9.0 $\pm$ 1.5
	Bimanual	10 $\pm$ 0	9.5 $\pm$ 1.0	8.5 $\pm$ 1.75
Stability [%]	Preferred	69.73 $\pm$ 9.17	25.73 $\pm$ 27.74	9.49 $\pm$ 15.79
	Non-preferred	71.81 $\pm$ 7.51	30.71 $\pm$ 29.84	8.17 $\pm$ 5.77
	Bimanual	62.95 $\pm$ 15.04	14.89 $\pm$ 15.32	1.26 $\pm$ 3.79
Accuracy [%]	Preferred	69.43 $\pm$ 1.45	53.09 $\pm$ 10.97	55.06 $\pm$ 35.82
	Non-preferred	69.03 $\pm$ 1.45	53.50 $\pm$ 8.36	54.59 $\pm$ 33.10
	Bimanual	70.45 $\pm$ 6.71	41.77 $\pm$ 21.64	34.15 $\pm$ 5.6
Monotonicity [μ_{bt}]	Preferred	0.96 $\pm$ 0.01	0.88 $\pm$ 0.17	0.75 $\pm$ 0.04
	Non-preferred	0.95 $\pm$ 0.01	0.95 $\pm$ 0.14	0.87 $\pm$ 0.22
	Bimanual	0.93 $\pm$ 0.04	0.77 $\pm$ 0.19	0.51 $\pm$ 0.28
Linearity [γ_{bt}]	Preferred	1.00 $\pm$ 0.00	0.98 $\pm$ 0.02	0.93 $\pm$ 0.09
	Non-preferred	0.99 $\pm$ 0.00	0.99 $\pm$ 0.01	0.85 $\pm$ 0.13
	Bimanual	0.99 $\pm$ 0.00	0.96 $\pm$ 0.02	0.63 $\pm$ 0.24

HEALTHY ADULT SUBJECTS All healthy adult subjects were able to complete all trials and collect all stars. Figure 3.7 shows the scores for healthy adult subjects. A Friedman test detected no significant influence of control mode on the accuracy scores ($\chi^2(2) = 4.08$, $P = 0.07$). Conversely, there was a significant influence of control mode on the stability ($\chi^2(2) = 14.33$, $P < 0.001$), monotonicity ($\chi^2(2) = 34.52$, $P < 0.001$) and linearity ($\chi^2(2) = 38.08$, $P < 0.001$) scores. A Nemenyi post hoc test revealed that the scores during the bimanual mode were generally lower than during the unimanual modes. No significant difference was observed between the unimanual preferred and unimanual non-preferred modes.

TD SUBJECTS All TD subjects were able to complete all trials and collect all stars, except for a small number of subjects who missed one or two stars during the bimanual mode. Fig-

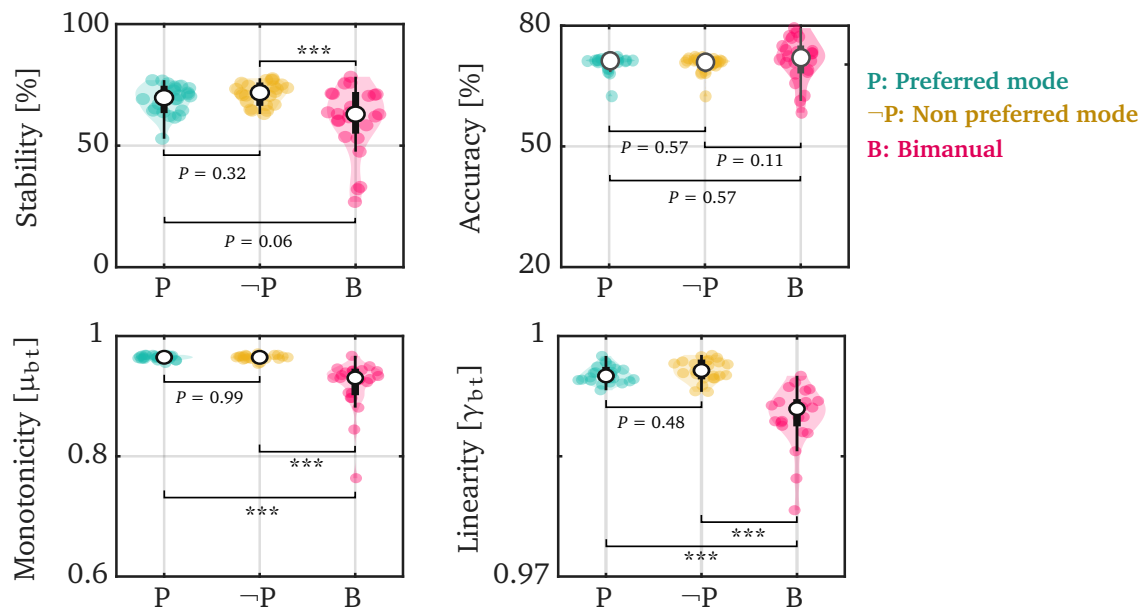


Figure 3.7 | The performance scores for healthy adult subjects. P refers to preferred, ¬P non-preferred and B bimanual. *** represents $P < 0.001$, ** $P < 0.01$ and $P < 0.05$.

Figure 3.8 shows the scores for TD subjects, as well as the correlation between their scores and age across all control modes. Due to the ceiling effect associated with the number of stars metric, no difference between control modes and no correlation between the number of stars and age were observed. A Friedman test revealed a significant influence of control mode on the stability ($\chi^2(2) = 27.56$, $P < 0.001$), accuracy ($\chi^2(2) = 10.56$, $P < 0.01$), monotonicity ($\chi^2(2) = 30.19$, $P < 0.001$) and linearity ($\chi^2(2) = 31.69$, $P < 0.001$) scores. A Nemenyi post hoc test revealed that, as expected, the stability, monotonicity and linearity scores during the bimanual mode were lower than during the unimanual preferred and unimanual non-preferred modes, while the accuracy scores during bimanual mode were lower than during the non-preferred mode. No significant difference was detected between the unimanual preferred and unimanual non-preferred modes, across all performance measures.

A Spearman's correlation coefficient test revealed a significant positive correlation between age and scores in all performance measures, across all three control modes, where the scores increased steadily with age. The correlations were generally stronger during unimanual control modes than the bimanual mode. A 10,000 bootstrap resampling of the slope of age vs. scores relationship was performed to investigate the difference in the rate of development between unimanual and bimanual control modes. As shown in Figure 3.9A, the slopes during the bimanual control mode were generally lower than during the unimanual modes.

As reviewed in Chapter 1, the development of motor skill is most rapid before the age of 8 years, and only become adult-like between 8 to 11 years (Forssberg *et al.*, 1991). Therefore,

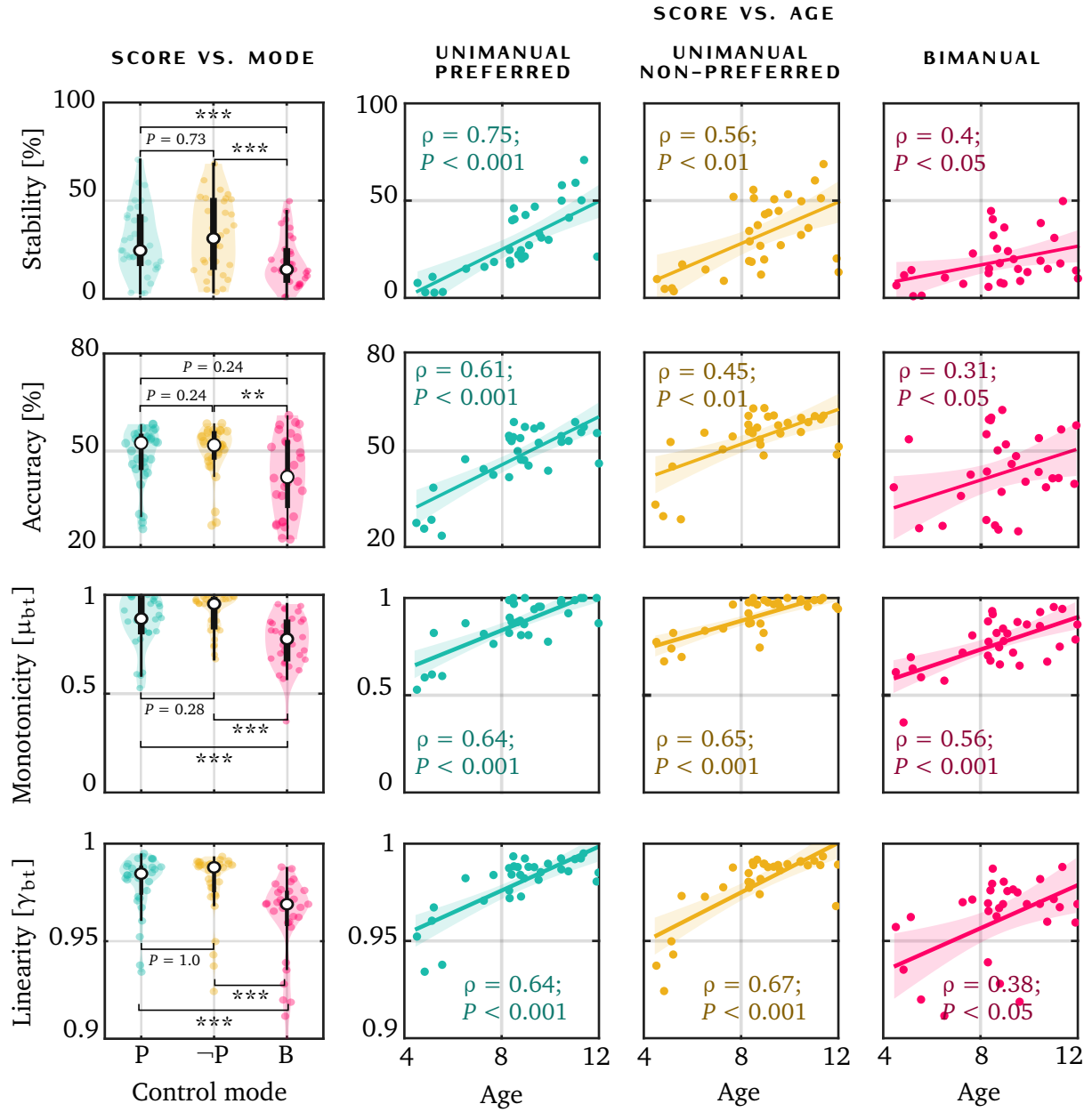
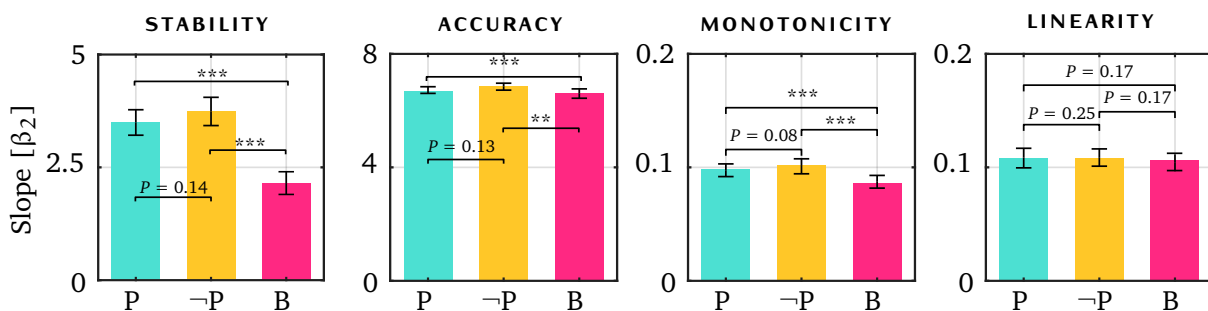


Figure 3.8 | The influence of control mode and age on stability, accuracy, monotonicity and linearity scores for TD subjects. Shown are the influence of control modes on the scores (column 1), and the results from the correlation analysis between age and the scores across all three control modes (column 2-4). The shaded area represents 95% confidence interval for the linear fit.

the differences in the rate of change of scores with respect to age, between younger (age < 8 yrs) and older (age > 8 yrs) subjects were explored. It can be seen in Figure 3.8 (e.g. the linearity scores during the unimanual non-preferred mode) that the rate of change of scores amongst younger subjects appears higher than older subjects. Figure 3.9B verifies this observation, by showing that the slopes of age vs. accuracy, monotonicity and linearity scores for younger subjects were significantly higher than older subjects, during all three control modes.

A. BETWEEN CONTROL MODES



B. BETWEEN YOUNGER AND OLDER SUBJECTS

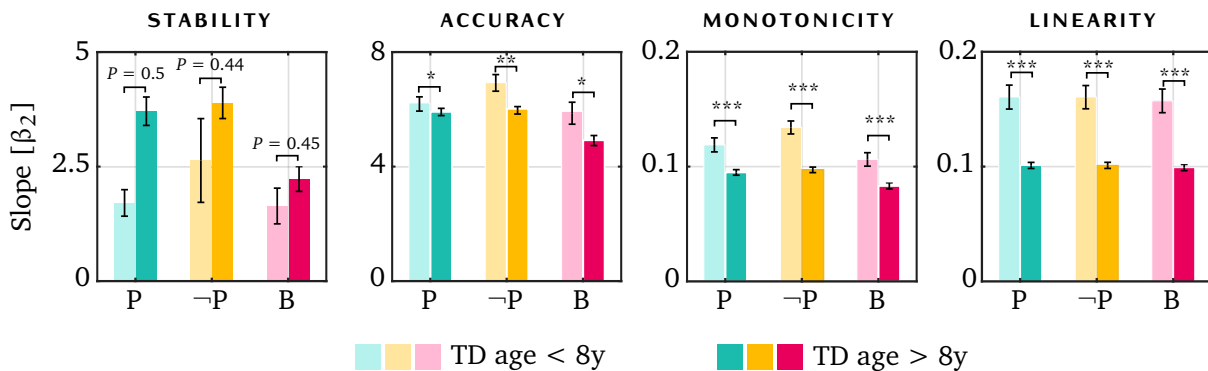


Figure 3.9 | The influence of control modes and TD age group, i.e. younger (age < 8 yrs; $n = 8$) vs. older (age > 8 yrs; $n = 24$), on the slope of age vs. scores relationship. Slopes are shown as mean and standard deviation calculated from 10,000 bootstrap samples. Significant differences between (A) control modes and (B) younger and older subjects' slope were calculated based on these bootstrap distribution.

SUBJECTS WITH USCP All subjects with USCP were able to complete all trials and collect all stars, except for a small number of subjects who missed one or two stars during the non-preferred and bimanual modes. Figure 3.10 shows the stability, accuracy, monotonicity and linearity scores for subjects with USCP, as well as the correlation between their scores and MACS level. A Friedman test revealed a significant influence of control modes on the stability ($\chi^2(2) = 8.62$, $P = 0.01$), accuracy ($\chi^2(2) = 9.36$, $P < 0.05$) and linearity ($\chi^2(2) = 7.14$, $P = 0.03$)

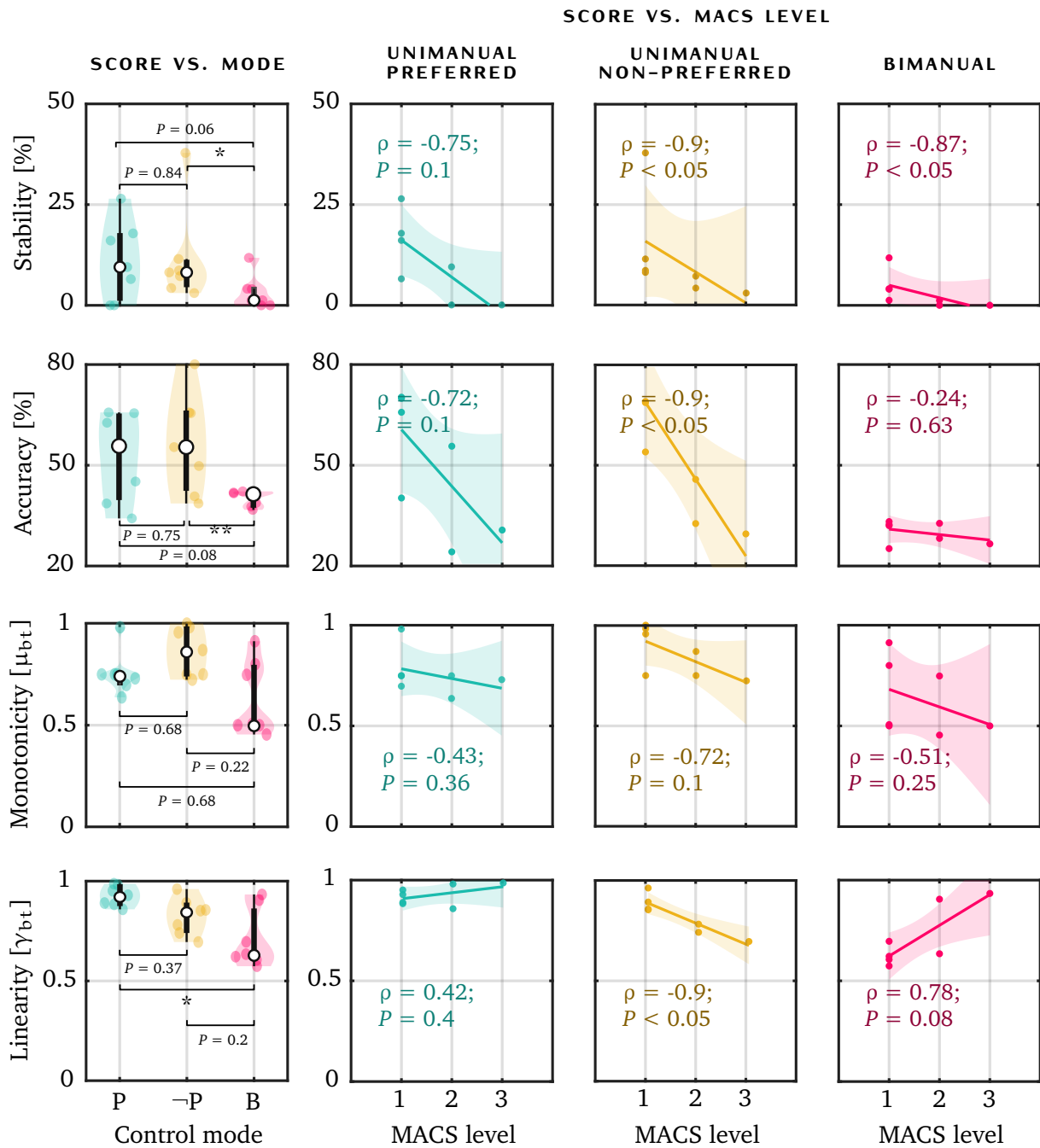


Figure 3.10 | The influence of control mode and MACS level on stability, accuracy, monotonicity and linearity scores for subjects with USCP. Shown are the influence of control modes on the scores (column 1), and the results from the correlation analysis between MACS level and the scores across all three control modes (column 2-4). The shaded area represents 95% confidence interval for the linear fit.

scores. No significant influence of control modes was detected on the monotonicity score ($\chi^2(2) = 2.77, P = 0.25$), although the scores during bimanual mode appear to be lower than during unimanual preferred and non-preferred modes.

The influence of MACS level on performance of subjects with USCP was investigated using a Spearman's correlation coefficient test. In most cases (8 out of 12), the test could not detect a significant correlation, potentially due to the low sample size. However, in general, the results show a clear trend towards a negative correlation between the scores and MACS level, where the scores decreased as the MACS level increases. Surprisingly, the negative correlation between scores and MACS level was observed not only in the unimanual non-preferred (affected side) and bimanual modes but also in the unimanual preferred (non-affected side) mode — although many previous studies showed that the non-affected side of children with USCP remains intact or only has subtle deficits (Odding *et al.*, 2006; Gordon *et al.*, 1999). Conversely, the linearity scores during the unimanual preferred and bimanual modes were positively correlated with MACS level, although insignificant.

A separate Spearman's correlation coefficient test revealed no significant correlation between age and the scores for subjects with USCP ($\rho \approx \pm 0.2; P > 0.2$ across all cases), suggesting that age may not have any influence on USCP's performance.

INTERGROUP COMPARISONS The performance differences between USCP, TD and adult subject groups were analysed using a Kruskal-Wallis test, which revealed a significant influence of group on the scores ($P < 0.001$ for all cases). A post hoc Dunn-Sidak test was computed to test the significant differences between every pair of groups, as shown in Figure 3.11. Overall, the scores for younger and older TD subjects were significantly lower than adults, in all control modes across all performance measures (except monotonicity scores during the unimanual modes). Similarly, the scores for subjects with USCP appear to have higher variability than TD subjects. They also generally appear to have lower scores than older TD subjects in all performance measures including during the unimanual preferred mode, albeit insignificant. Except for the linearity scores during the bimanual modes, the scores for subjects with USCP remained within the range of their younger TD counterparts.

ADDITIONAL ANALYSIS ON TEMPORAL COORDINATION DURING BIMANUAL MODE

A previous study by Steenbergen *et al.* (2008) noted that, when performing a bimanual (uncoupled) task, the non-affected hand of children with USCP slowed down to match the speed of the affected hand, compared to during a unimanual task. To investigate if a similar effect exists in this experiment, an additional analysis was performed by calculating the temporal discrepancy between the onset of preferred T_P and non-preferred T_{-P} hands when initiating the task in during the bimanual mode. The onset was determined by detecting the first point where the balloons have moved 5% of their full trajectory during bimanual control mode. The onset discrepancy T_o was then calculated from the difference in onset between the preferred and non-preferred hands, $T_o = T_P - T_{-P}$.

A paired, non-parametric Wilcoxon signed-rank test revealed neither groups displayed preference towards initiating the movement with preferred or non-preferred hand (Figure 3.12A). An independent, non-parametric Mann-Whitney U test was performed to measure the difference in the absolute onset discrepancy between TD and USCP subjects, and found no difference between these two subject groups (Figure 3.12B, non-absolute comparison $P = 0.43$). There was a no correlation between the absolute onset discrepancy and age for TD subjects ($\rho = -0.18$, $P = 0.31$), or between the absolute onset discrepancy and MACS level for subjects with USCP ($\rho = 0.24$, $P = 0.59$). No difference in the absolute onset discrepancy between TD subjects below and above 8 years ($P = 0.20$).

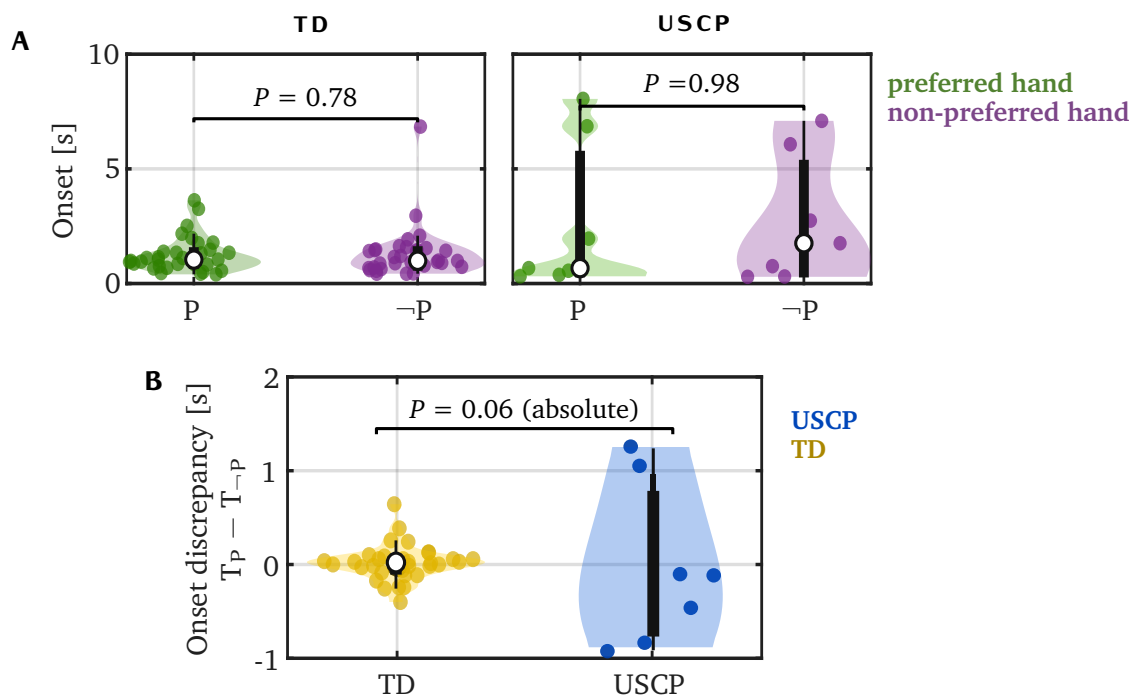


Figure 3.12 | The onset of movement for TD and USCP subjects. Shown are **A.** the onset of movement of preferred and non-preferred hands, and **B.** the onset discrepancy between preferred and non-preferred hands.

3.4 INFLUENCE OF PERTURBATION ON BIMANUAL CONTROL

To understand how children adjust and adapt their grip force during incongruent bimanual coordination, perturbation was added to the bimanual mode of the previous experiment. Each subject played a total of 14 trials. In 6 of these trials, one of the hands was perturbed by increasing the sensitivity of the grip force-to-height mapping by threefold. The difference in grip force sensitivity between the perturbed and unperturbed hands, as well as the arrangement of the trials, is illustrated in Figure 3.13.

The recruited subjects for this experiment were the same subjects from the previous experiment. This experiment was conducted following a 30-minute to 1-hour break after completing the first experiment. At least one parent/guardian accompanied subjects below 18. Verbal assent was obtained from the subjects as to whether they agree to participate in the second part of the experiment, and 2 of 32 TD subjects declined to continue. Therefore, the final set of subjects consists of 30 TD children (mean age 8.80 yrs, standard deviation 2.01 yrs; range 4.52 - 11.98 yrs; 15 M 15 F; 26 right-handed) and 7 children with USCP (mean age 10.84 yrs, standard deviation 2.81 yrs; range 7.54 - 15.04 yrs; see Table 3.1 for subjects with USCP' biographical information) participated in the experiment. The experiment was approved by the Imperial College Research Ethics Committee (UK), University of Sultan Zainal

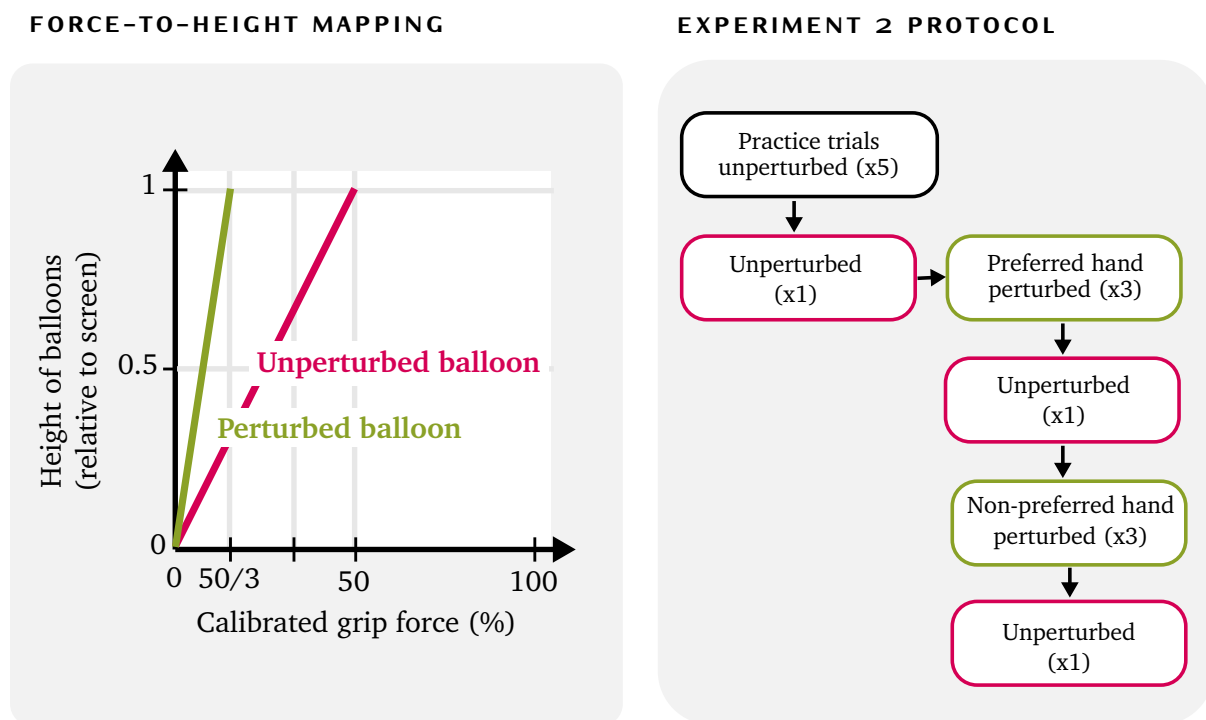


Figure 3.13 | **Investigating bimanual grip force control during an incongruent bimanual task.** The perturbation was implemented by increasing the sensitivity of the grip force-to-height mapping by threefold.

Abidin Human Research Ethics Committee (Malaysia) and National Health Group Domain Specific Review Board (Singapore).

The game data (i.e. time, game frame and x - and y -trajectories of the balloons, target and buddy), the game-dependent performance measures (i.e. accuracy and stability scores) and the grip-force signals from the GripAble were recorded at 70 Hz, through a custom data collection thread running within the game.

3.4.1 Data analysis

A preliminary analysis of the data suggests that most subjects were able to perform the experiment. However, some TD and USCP subjects were only able to complete the first half of the trial (i.e. upward movement), especially during the perturbed trials, without proceeding to downward movement due to the 50-seconds time-out. Therefore, data analysis for this experiment utilised only the upward movement for each trial.

The first five unperturbed trials were considered practice trial and were excluded from data analysis. The data analysis for this experiment is similar to the previous experiment, where the performance of each subject was measured in term of stability, accuracy, monotonicity and linearity scores. On top of these scores, the peak onset velocity at the onset of movement was measured for each hand. The velocity was measured from the first derivative of the balloons' trajectories. The peak onset velocity was then obtained from the maximum velocity within the first two seconds (140 frames) of the movement, which was calculated separately for each hand.

Due to the relatively small sample sizes, non-Gaussian distributions of the variables of interest, and an intra-subject design, non-parametric statistical tests were used throughout this experiment for testing performance differences between the trials. The overall influence

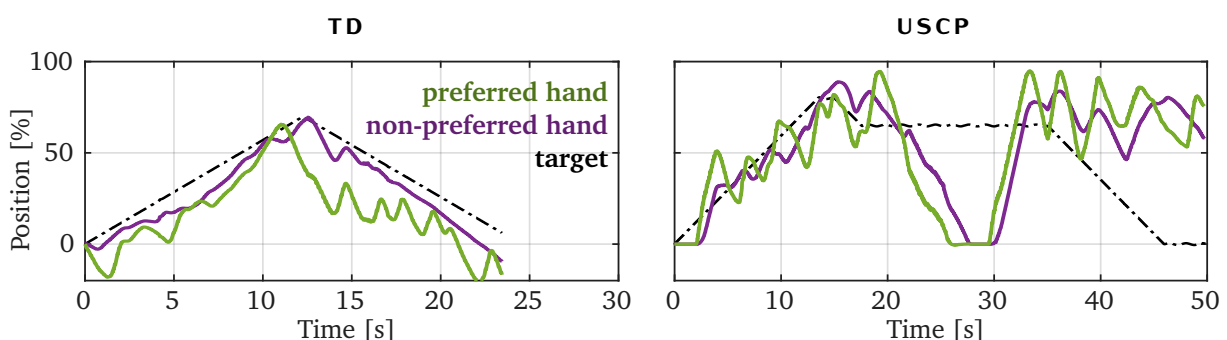


Figure 3.14 | Example signals during the incongruent bimanual experiment from one TD and USCP subjects. Shown are signals from one TD subject age 9.9 yrs and one USCP subject age 11.8 yrs during the preferred perturbed trial (trial 3). Both figures show the target's trajectory (dashed black line), as well as the balloon's trajectories of the preferred hand (green line) and the non-preferred hand (purple line). USCP subject shown here did not complete the downward movement.

of trial on the scores was analysed using a Friedman test. The statistical difference between every pair of trials was analysed using a post hoc Nemenyi test (36 pairs in total), following a significant χ^2 test. A Mann-Whitney U test was computed on the pooled data of all trials to determine the significant differences between the performance of TD and USCP groups. Statistical significance was calculated at 95% confidence level.

3.4.2 Results

Table 3.3 gives the median $\pm$ interquartile range of the scores during unperturbed and perturbed trials. Overall, all TD and USCP subjects were able to complete the upward movement of every trial within 50 seconds time limit and collect all stars, except for a small number of subjects who missed one or two stars. A Mann-Whitney U test of the pooled data from all trials between TD and USCP subjects revealed that the stability and linearity scores for subjects with USCP were lower than their TD counterparts ($P < 0.001$ for stability; $P < 0.05$ for linearity). Conversely, no significant difference was observed in the monotonicity ($P = 0.07$) and accuracy scores ($P = 0.11$) between TD and USCP subjects.

Figure 3.15 shows the performance scores for TD and USCP subjects across all 9 trials. For TD subjects, a Friedman test revealed that there is a significant influence of trials on stabil-

Table 3.3 | The performance of all subjects. Shown are the median $\pm$ interquartile range scores across all perturbation types (non-preferred hand perturbed, preferred hand perturbed and unperturbed) during the incongruent bimanual experiment.

Performance measure	Group	Unperturbed	Preferred hand perturbed	Non-preferred hand perturbed
Number of stars [#]	TD	5 $\pm$ 0	4 $\pm$ 1	4.5 $\pm$ 0.75
	USCP	4.25 $\pm$ 1	4.25 $\pm$ 1	4 $\pm$ 0.75
Stability [%]	TD	43.60 $\pm$ 10.17	13.24 $\pm$ 4.48	14.80 $\pm$ 8.23
	USCP	10.64 $\pm$ 5.28	3.59 $\pm$ 0.96	2.19 $\pm$ 0.18
Accuracy [%]	TD	18.54 $\pm$ 0.89	15.95 $\pm$ 1.18	16.53 $\pm$ 0.53
	USCP	13.25 $\pm$ 3.97	9.30 $\pm$ 1.58	13.26 $\pm$ 4.02
Monotonicity [μ_{bt}]	TD	0.97 $\pm$ 0.07	0.78 $\pm$ 0.04	0.76 $\pm$ 0.10
	USCP	0.80 $\pm$ 0.08	0.62 $\pm$ 0.05	0.69 $\pm$ 0.04
Linearity [γ_{bt}]	TD	0.98 $\pm$ 0.01	0.96 $\pm$ 0.02	0.96 $\pm$ 0.01
	USCP	0.96 $\pm$ 0.02	0.91 $\pm$ 0.01	0.94 $\pm$ 0.02
Peak velocity [cm/s] preferred hand	TD	2.57 $\pm$ 0.11	3.63 $\pm$ 0.14	2.54 $\pm$ 0.21
	USCP	2.48 $\pm$ 0.81	3.92 $\pm$ 0.35	3.04 $\pm$ 0.70
Peak velocity [cm/s] non-preferred hand	TD	2.65 $\pm$ 0.14	2.57 $\pm$ 0.19	3.47 $\pm$ 0.40
	USCP	2.19 $\pm$ 0.37	2.63 $\pm$ 0.08	3.08 $\pm$ 0.62

ity ($\chi^2(8) = 82.5$, $P < 0.001$), accuracy ($\chi^2(8) = 17.78$, $P < 0.05$), monotonicity ($\chi^2(8) = 59.88$, $P < 0.001$) and linearity ($\chi^2(8) = 47.57$, $P < 0.001$) scores, implying that perturbation has a significant effect on the bimanual control of TD children. A post hoc Nemenyi test on every pair of trials demonstrated that, in general, their scores during the perturbed trials were significantly lower than the unperturbed trials. No significant difference was observed between every pair of unperturbed trials (i.e. 1st and 5th, 5th and 9th, 1st and 9th), across all performance measures.

For subjects with USCP, a Friedman test revealed a significant influence of trials on, monotonicity ($\chi^2(8) = 14.33$, $P < 0.05$) and linearity ($\chi^2(8) = 15.61$, $P < 0.05$) scores. A post hoc

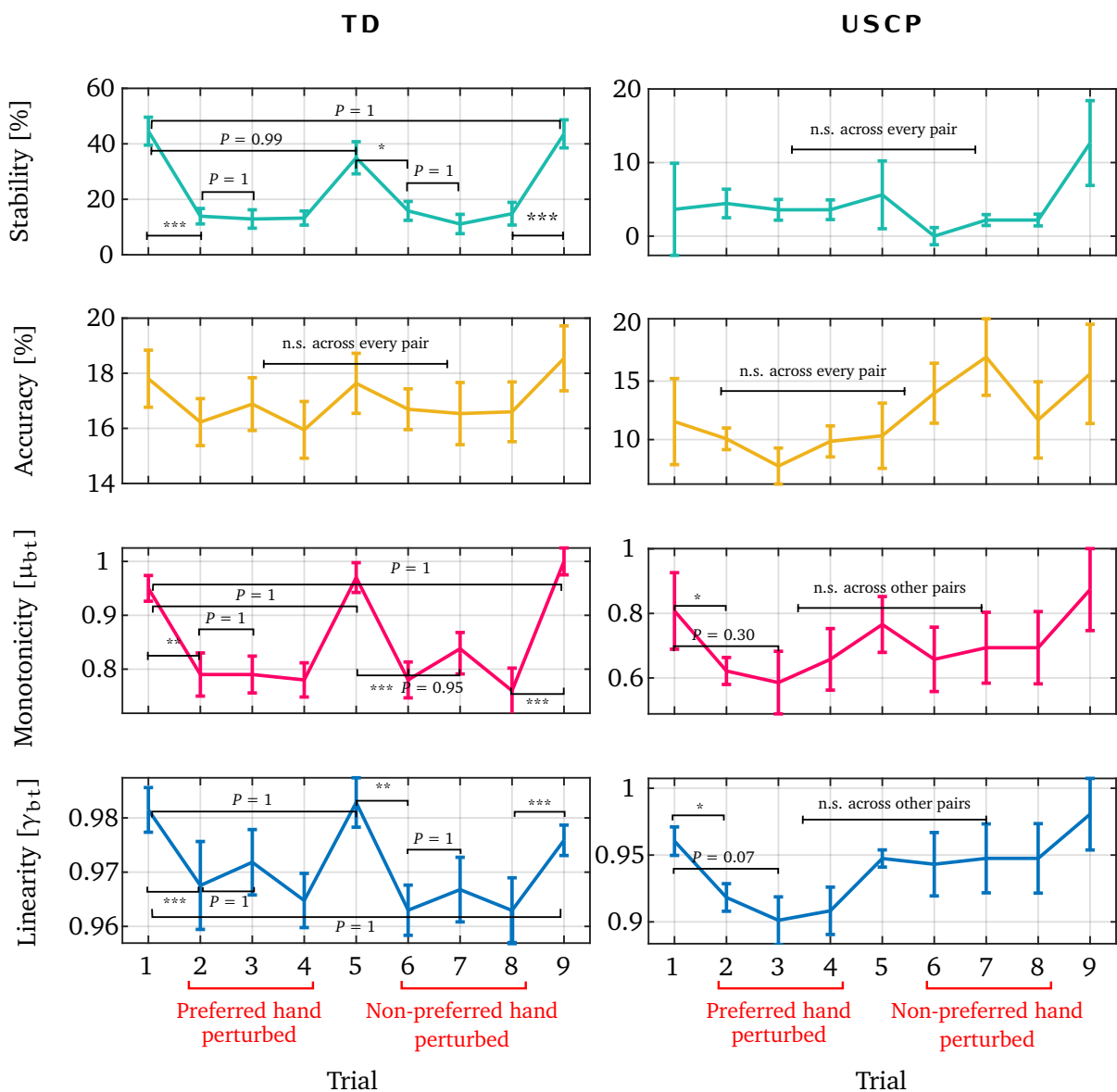


Figure 3.15 | The influence of perturbation on bimanual grasp control. Trial 1, 5 and 9 are unperturbed. The preferred hand was perturbed in trial 2, 3, and 4, whereas the non-preferred hand was perturbed in trial 6, 7 and 8. *** represents $P < 0.001$, ** $P < 0.01$, $P < 0.05$ and n.s. not significant.

Nemenyi test demonstrated a significant difference in the monotonicity and linearity scores between only the first and second trials. No similar effect was observed on the stability ($\chi^2(8) = 10.07$, $P = 0.26$) and accuracy ($\chi^2(8) = 6.57$, $P = 0.58$) scores.

Figure 3.16 shows the influence of perturbation on the peak onset velocity for TD and USCP subjects. A Friedman test, followed by post hoc Nemenyi test on TD subjects' data demonstrated a significant change in the peak onset velocity of both dominant ($\chi^2(8) = 93.21$, $P < 0.001$) and non-dominant ($\chi^2(8) = 63.75$, $P < 0.001$) hands when perturbation was applied on the corresponding sides, while the contralateral, unperturbed hand showed no reaction.

For subjects with USCP, there was a significant increase in the peak onset velocity of their non-affected hand, following a perturbation on this hand ($\chi^2(8) = 25.58$, $P < 0.01$), while the contralateral unperturbed hand remained unchanged. Similarly, there was a significant influence of perturbation on the peak onset velocity of their affected hand ($\chi^2(8) = 29.1$, $P < 0.001$). However, the perturbation applied on this hand triggered a synergistic increase in the peak onset velocity from both affected and non-affected hands.

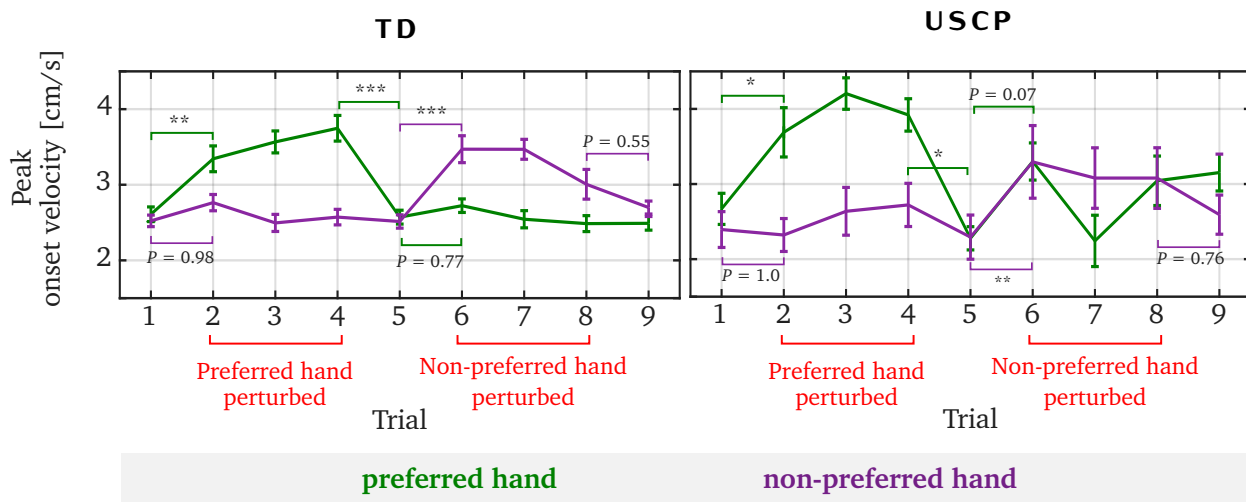


Figure 3.16 | **Peak velocity at the onset of movement.** Shown are the peak velocity at the onset of balloons' movements for the preferred and non-preferred hands, across all trials.

3.5 DISCUSSION

This chapter presents two studies that investigated the grip coordination and motor planning of TD children and children with USCP during unimanual and visually-coupled bimanual tasks. The first experiment stratified the typical and atypical development of unimanual and visually-coupled bimanual control in 32 TD children between 4.5 to 12 years, as well as on 7 children with USCP with different MACS levels. The second experiment examined how these children maintained their grip scaling when one of the hands was perturbed and investigated whether they were able to recover their original strategy when the perturbation was removed. Both experiments were carried out using the Bimanual Balloon Buddy game. During this game-based experiment, subjects controlled two virtually connected game objects, by gradually increasing and releasing their grip forces through the GripAble device (see Chapter 2.1.1), to follow a slow-moving target and ultimately collect points.

TYPICAL AND ATYPICAL DEVELOPMENT OF GRIP CONTROL The results from the first experiment can be summarised into: (1) TD subjects exhibited non-linear refinement of motor control with age, (2) the development of bimanual control is slower than unimanual, (3) TD and USCP subjects, as well as healthy adults, exhibited worse bimanual coordination than unimanual coordination, (4) the performance of subjects with USCP deteriorated with higher MACS level, with the deterioration equally observed in their non-affected hand, and (5) subjects with USCP displayed a simultaneous movement initiation from both hands, suggesting that visual coupling could potentially encourage the two hands to move in concert.

The results highlight that the grip control of TD children during unimanual and bimanual movements are not innate, supporting previous studies looking into the development of motor skills in children (e.g. Forssberg *et al.*, 1991; Forssberg *et al.*, 1992). Specifically, the motor skills of TD subjects became more integrated and efficient, and exhibited less variability with age. The monotonicity of their grip force generation (particularly during bimanual mode) also increased with age, suggesting the development of temporal coupling of the two hands to follow the target in concert. These skills evolved rather asymptotically, where older TD subjects exhibited slower refinement compared to their younger counterparts. These findings are in concordance with the literature that demonstrated how children of age 3 - 6 make significant advances in gross and fine motor skills, due to increased coordination as the parts of the brain responsible for sensory and motor skills develop. By the age of 8 - 11, their sensorimotor function matures, and most children will have gained good enough skills required by everyday tasks. Thus, their motor development continues rather slowly until they attain an adult-like dexterity in early teenage years (Forssberg *et al.*, 1991; Eliasson, 2006).

Bimanual actions involve many unique coordination properties. Each raises interesting questions as to how the action is organised in the central nervous system. In this study, all subjects, including healthy adults, displayed poorer bimanual control than unimanual despite the presence of visual coupling between the two hands. Furthermore, the bimanual control of TD subjects developed slower than unimanual control. This is natural given that two-handed tasks are generally more difficult to coordinate. These tasks often demand higher visual-temporal processing that requires a longer learning process before mastery. Furthermore, to generate coordinated grip forces from both hands, the dynamics of each hand needs to be temporally and spatially orchestrated (Steenbergen *et al.*, 2008). Notably, in this experiment, subjects' grip force was further constrained by the speed of a moving target, thereby requiring them to precisely, yet simultaneously, scale their grip force magnitude from both hands to match the target. This additional constraint potentially provided more scope for error that, perhaps, the shared visual feedback could not compensate for.

Despite poorer performance during bimanual control, this study discovered some evidence for the potential of visual feedback in facilitating temporal coordination in subjects with USCP. As a comparison, a previous study by Steenbergen *et al.* (2008) demonstrated that (uncoupled) bimanual movement hindered the temporal coordination of subjects with USCP, where they took a longer time to initiate the movement of their non-affected hand during a bimanual task, compared to an equivalent unimanual task. However, the results of the present experiment show no significant difference in the onset discrepancy between their affected and non-affected hands, and their onset discrepancy was within the range of their TD counterparts. Therefore, it is tempting to speculate that these results reflect the influence of visual feedback in giving the impression of modulating the same object at the same time, which prompts one's inherent tendency towards initiating the movement of both hands more cohesively. However, the insignificant movement onset between the two hands could also be due to the nature of the task itself, which dictates the speed of grip movement through a reference target, thus triggering a 'countdown' effect for both hands to be initiated simultaneously. This may be a reflection of the same effect as previously observed by Sugden & Utley (1995a), where the affected hand of subjects with USCP sped up when they were instructed to perform a bimanual movement as fast as possible (see also Steenbergen *et al.*, 1996; Utley & Sugden, 1998; Steenbergen *et al.*, 2000, who found the opposite results). However, given the high variance displayed by subjects with USCP, a larger data set is needed to verify these hypotheses.

Mounting evidence in the literature has shown impaired unimanual and bimanual coordination in USCP, particularly during precision grip tasks (Eliasson *et al.*, 1991; Gordon *et al.*, 1999; Steenbergen *et al.*, 2008), or reaching tasks (Sugden & Utley, 1995a; Hung *et al.*, 2004). The results from the present study provide further evidence on the nature and extent

of sensorimotor impairment in children with USCP, in a different context. Similar to Eliasson *et al.* (1991)'s findings, subjects with USCP exhibited poor grip coordination, where their performance was similar to, or more exaggerated than, that found in younger TD subjects during both unimanual and bimanual tasks. Furthermore, as expected, their performance deteriorated with higher MACS level. Surprisingly, this deterioration was also observed in their non-affected hand, although the non-affected side of children with USCP was previously shown to remain intact, or possesses only subtle deficits (Odding *et al.*, 2006; Gordon *et al.*, 1999). On top of that, their performance was not age-dependent, suggesting that children with USCP may be suppressed a limited range of activities to experience motor learning. To explain these results, one may need to re-observe how children with USCP perform their everyday tasks. Most of our ADLs involve coordinated use of both hands. However, children with USCP are restricted to perform all activities using only their non-affected side, owing to the limited capacity of their affected hand. As such, the skills they can acquire from using their non-affected side alone may be less dexterous than that of two-handed tasks. In order for children with USCP to perform a more complex task, some of them even have to resort to a 'compensatory strategy' by using their other body parts, such as elbow and teeth, for assistance (Adler *et al.*, 2015). As their MACS level increases, their range of activities becomes narrower, thereby suppressing their upper limb capacity, including that of their non-affected hand, to a poor, unrefined level.

HOW PERTURBATION MODIFIES GRIP CONTROL The results from the first experiment have provided a basic understanding of how visually-coupled bimanual coordination develops and manifests under both TD and USCP conditions. Using the knowledge gained from this experiment, the second experiment proceeded to explore how TD and USCP subjects modified their grip control in response to a perturbation. Specifically, the sensitivity of the grip force from one of the hands was increased by threefold in between unperturbed trials, thereby making the grip control demanded by each hand incongruent.

Collectively, the main findings from this experiment can be summarised into: (1) both TD and USCP subjects showed a distinct response when perturbed, (2) the grip coordination of TD subjects deteriorated following a perturbation, however, they were able to recover their baseline (unperturbed) coordination in the subsequent unperturbed trial, (3) the coordination of the non-affected hand of subjects with USCP demonstrated similar response as observed in TD subjects, and (4) the perturbation of the affected hand of subjects with USCP triggered a synergistic response from their non-affected hand.

Anticipatory (i.e. feedforward) control in humans is a process that involves the nervous system to efficiently use sensory information to integrate and store information for internal or memory representation of an object (Eliasson *et al.*, 1992). This internal representation

is formed through tactile and proprioceptive signals during earlier manipulatory experience (Johansson & Westling, 1988; Forssberg *et al.*, 1992). The results from this experiment corroborate previous studies by Forssberg *et al.* (1992), where TD subjects exhibited significant deterioration following an unexpected perturbation (i.e. lower scores for all variables of interest), suggesting an intact anticipatory control. However, despite the poor performance during the perturbed trials, TD subjects can immediately regain their baseline (unperturbed) performance, and adjust the peak velocity once the perturbation is removed. This suggests a preserved internal control model which was not entirely ‘tainted’ by their sensorimotor memory formed prior to the movement (during the perturbed trials). Specifically, these children are also able to perform an ‘on-line’ adjustment of their grip force based on the ongoing task demands. Unfortunately, since Forssberg *et al.* (1992) did not re-test their subject’s original grip coordination after the ‘perturbed’ setting, this experiment could not compare whether their subjects exhibit similar ability to regain their ‘unperturbed’ coordination.

In contrast, the performance of subjects with USCP showed a larger variability in persistent, noisy, and random motor patterns. These children demonstrate deteriorated performance (i.e. lower monotonicity and linearity), coupled with an eminent increase in peak onset velocity following an unexpected perturbation on their non-affected hand. Similar to TD subjects, subjects with USCP can regain their baseline coordination once the perturbation on the same hand was removed. Conversely, the performance of their affected hand did not show a deterioration following a perturbation. This effect may be due to impaired motor planning in children with USCP, where they are constrained to using immature movement strategies in which forces are not prepared in a feedforward manner. On top of that, the perturbation applied on their affected hand triggered a synergistic response from their non-affected hand. Specifically, there was an overlap of responses from their preferred and non-preferred hands, potentially reflecting a compensatory mechanism to increase joint stability and cope with poorer motor control on the affected side. An alternative explanation of these results is that some children with USCP exhibit an ipsilateral projection to control the upper extremities (Staudt *et al.*, 2002; Holmström *et al.*, 2010). These children often have the most severe impairments of the hand function compared to those with typical, contralateral projection or mixed projection (Holmström *et al.*, 2010). They also have reduced white matter integrity of the corpus callosum (Weinstein *et al.*, 2014) that results in the persistence of mirror movements. Therefore, it is possible that the observed synergistic response may reflect the unintended mirror movement that accompanies voluntary activity in homologous muscles on the opposite hand. However, since this study did not assess the subjects’ corticospinal projection and callosal integrity, the pathomechanism underlying their impaired performance cannot be tested.

Collectively, the significant reaction to perturbation observed on the non-affected side of subjects with USCP suggests an intact sensory function and anticipatory control of the non-affected side — thereby contradicting the previous hypothesis about immature movement strategy amongst children with USCP. Specifically, they were able to sense and anticipate an appropriate amount of the grip force and adjust this force configuration based on their previous manipulatory experience, similar to that observed in their TD counterparts (Steenbergen *et al.*, 1998; Forssberg, 1999; Gordon *et al.*, 1999; Mutsaerts *et al.*, 2006). These children may have had enough practice to develop their anticipatory control (Gordon & Duff, 1999) within the first six unperturbed trials. These results simultaneously suggest that:

1. the poor performance of the non-affected hand of subjects with USCP relative to their TD counterparts (in Experiment I) could be due to weak muscles or subtle spasticity on this side, which is exacerbated by higher MACS level (Sugden & Utley, 1995b).
2. the unclear reaction to perturbation and high variability of motor output in the affected hand (in Experiment II) may not be due to impaired motor planning; rather, they may reflect the typical impairments associated with USCP, including (i) *impaired tactile feedback* from mechanoreceptors in the skin and joint (Krumlinde-Sundholm & Eliasson, 2007) that impedes their ability to estimate the amount of grip forces onto the hand-grip devices; (ii) *impaired motor control*, which disturbs the temporal coordination and amplitude of muscle activity (Klingels *et al.*, 2012). This factor is further made plausible since most subjects with USCP exhibited moderate to severe pronators and wrist flexor muscles spasticity (i.e. Modified Ashworth Scale 1+ to 3). They also exhibited low monotonicity scores throughout the experiment, suggesting a frequent grasp-ungrasp oscillation that could be attributable to low muscle strength (Hamilton *et al.*, 2004); or (iii) *impaired sensorimotor integration* of the affected hand, i.e. unable to utilise the sensory information to produce an appropriate motor output (Gordon *et al.*, 2006a).

Nevertheless, due to the high variability and small sample size, a larger set of data is needed to properly elucidate these findings.

In conclusion, the two experiments in this chapter provide an initial understanding of normal and impaired coordination during unimanual and visually-coupled bimanual grip control amongst TD children and children with USCP. The novelty of the task lies in (1) the presence of visual coupling between the two hands that influences bimanual interaction, and (2) how the task demands a coordinated scaling of grip force with respect to its temporal evolution, as the hand was constrained by the dynamic of a reference target. Although the evidence for the benefit of visual feedback observed in this study may be inadequate, these findings could serve as a basis to instigate studies that aim to uncover the potential of visual feedback in facilitating bimanual control, especially for individuals with bimanual deficits such as children with USCP.

4 | HAPTICALLY-COUPLED BIMANUAL COORDINATION

This chapter is adapted from:

Sharah A Mutalib, Michael Mace & Etienne Burdet. Bimanual coordination during a physically coupled task in unilateral spastic cerebral palsy children. *Journal of NeuroEngineering and Rehabilitation* **16**, 1 (2019). URL: <https://doi.org/10.1186/s12984-018-0454-z>

The previous chapter has unveiled how TD children, children with USCP and healthy adults control their grip force generation and scaling during unimanual and visually-coupled bimanual tasks. The results from both experiments demonstrated that even with a visual connection between the two hands, the grip coordination during bimanual control remains less coordinated than during unimanual control, similar to that found during uncoupled bimanual tasks (e.g. Gordon *et al.*, 1999; Steenbergen *et al.*, 2000; Steenbergen *et al.*, 2008). However, despite the poorer coordination during the visually-coupled bimanual task, there might be a potential benefit of visual feedback for children with USCP, particularly in ‘giving rise’ to the impression of controlling a single object instead of two, that could have decreased the difference in the onset of movement between their affected and non-affected hands.

This chapter continues the elucidation of bimanual coordination during physically-coupled tasks, by exploring the potential of *haptic feedback* in facilitating the bimanual grip control of TD and USCP children. Haptic feedback is vital for the spatial and temporal coordination between the two limbs, regardless of age or impairment (Contu *et al.*, 2016). Despite its significance, most bimanual coordination research on children with USCP has focused on the uncoupled bimanual tasks alone. In contrast, the ubiquitous haptically-coupled bimanual tasks, where the two hands are mechanically connected to a single object, have never been explored in USCP populations. Many mechanically connected tasks, such as opening a screw-top jar or moulding a snowball, involve the exertion of equal and opposing forces onto a single shared object. Such actions can yield haptic feedback between the hands, in the form of *kinaesthetic* and *tactile* (cutaneous force) information that may facilitate and enhance haptic estimates (Iyengar *et al.*, 2007). This facilitation

has been encountered by some studies on unilateral stroke patients, which demonstrated an improved overall smoothness, speed and precision of movement when performing a bimanual task with both hands haptically-coupled (Sanguineti *et al.*, 2009; Contu *et al.*, 2016). Besides supplying the interaction forces between the two hands, a haptically-coupled task could also allow the non-affected hand to gather additional proprioceptive information to assist the ongoing movement of the affected hand (Sanguineti *et al.*, 2009). However, it is unknown whether this type of task could yield similar benefits for children with USCP, and is, therefore the focus of the present chapter.

This chapter explores the functional influence of haptic communication between two mechanically (and thus haptically) connected hands on the bimanual coordination of TD and USCP children. This coordination is investigated in an experiment that examines bimanual performance during a simple *single-object lifting task*. Of particular interest is the elucidation of how children with USCP would coordinate the two hands in a concerted temporal, force and kinematic manner, to manipulate the shared object. The guiding hypothesis for this experiment is that manipulating a single object with two hands could off-load the processing of force and kinaesthetic information onto the ipsilateral side. As such, by providing this ‘real-time’ haptic information from the non-affected side, this ‘ipsilateral strengthening’ of sensorimotor activation can compensate for the impaired sensory function omnipresent amongst children with USCP, and help these children to improve the anticipation and force coordination of an ongoing movement. Moreover, considering that some children with USCP are biased towards their non-affected side during ADLs while neglecting their affected side — a phenomenon known as developmental disregard (Taub *et al.*, 2004) — it is possible that ‘physically enforcing’ both hands to work together in a natural way could present a simple method of ‘unlocking’ the potential functionality of the affected limb.

4.1 HAPTICALLY-COUPLED LIFTING TASK

The haptically-coupled bimanual coordination amongst TD and USCP children was investigated in a simple bimanual lifting task using the Cube. As described in Chapter 2.1.2, the Cube is a 100 mm x 100 mm x 100 mm device that is equipped with a force transducer on each of its faces, to measure grasp forces as well as its interaction with the table.

A total of 32 children participated in this experiment. The *experimental group* consisted of 15 children with USCP (mean age 8.7 yrs, standard deviation 2.7 yrs, range 4.8 - 13.5 yrs; see Table 4.1 for participant information). The *control group* consisted of 17 TD children (mean age 8.2 yrs, standard deviation 2.5 yrs; range 4.4 - 13.8 yrs; 7 M 10 F; 17 right-handed) with no known medical disorders or history of neurological or musculoskeletal problems. During

Table 4.1 | Descriptive information for the subjects with USCP for the haptically-coupled bimanual lifting experiment. Spasticity level was assessed at the wrist using the Modified Ashworth Scale ranging from 0 to 4 (Bohannon & Smith, 1987). The tactile sensibility was measured using a two-point discrimination test and the results were interpreted as 3 mm = typical, 7 mm = decreased, and > 7 mm = impaired (Krumlinde-Sundholm & Eliasson, 2007). M, male; F, female; T, typical; D, decreased; I, impaired.

Subject	Sex	Age (yrs)	Hemiparetic side	Spasticity (wrist flexors)	MACS level	Tactile sensibility
1	F	9.5	Left	0	1	T
2	F	10.9	Right	1	1	D
3	F	4.8	Right	1+	2	I
4	F	13.5	Left	1+	2	D
5	M	9.1	Right	2	3	D
6	M	11.0	Left	2	3	I
7	F	5.5	Right	1+	2	I
8	F	9.3	Left	1	1	T
9	M	10.1	Left	2	1	D
10	M	5.0	Right	1	1	T
11	M	11.1	Left	1+	2	D
12	M	8.9	Left	1	3	I
13	M	11.2	Left	2	3	D
14	M	5.9	Left	1+	2	I
15	M	5.5	Right	1	2	I

recruitment, subjects were selected to ensure that the means and standard deviations of the two groups were similar. All subjects gave their assent, and informed consent was obtained from the accompanying parent. The experiment was approved by the Imperial College Research Ethics Committee (UK) for TD subjects and the University of Sultan Zainal Abidin Human Research Ethics Committee (Malaysia) for TD and USCP subjects.

The inclusion criteria subjects with USCP include diagnosed as ‘unilateral spastic’ according to the SCPE, MACS level of I-III (refer to Appendix A for the criteria of ‘unilateral spastic’ CP and the description of MACS levels), no mirror movement, the ability to grasp and lift the Cube with both hands and to follow instructions. To test the mirror movement of subjects with USCP, a short unimanual reaching and grasping test was conducted on the non-affected hand, while observing the mirror-symmetric activity on the affected hand. None of the subjects exhibited overt mirror movements during unimanual movements.

The experiment was conducted individually in a quiet room with minimal distractions. Each subject was seated comfortably on a chair in front of a table where the Cube was placed. The chair was adjusted in height to have the forearms horizontal when the Cube was grasped. Before the data recording, the force signals from the Cube were zeroed when on the table, to remove the spurious offsets and the interaction between the bottom force sensor and the

table. Each subject was asked to squeeze the Cube as hard as possible, in order to record the subject's maximum grasp strength. Subjects were then instructed to *grasp* the Cube with both hands, *raise* it vertically for approximately 8-10 cm, *hold* for 1-2 seconds, and then *deposit* back to the start position. The movements were demonstrated prior to data collection. A total of 15 self-paced trials were recorded, with a 10-second interval between trials. The first five trials were considered practice trials and excluded from the data analysis.

4.2 DATA ANALYSIS

As visualised in Figure 4.1, grasp force F_G was measured from the average forces applied on the left and right side of the Cube, $F_G = (F_{G,l} + F_{G,r})/2$, and load (tangential) force F_L was measured from the interaction between the bottom face of the Cube and the table. Grasp force rate F_{GR} was obtained from the first numerical differentiation of F_G signal. All signals from the left, right and bottom force sensors, as well as the linear acceleration signal from the IMU were filtered using a 4th order low-pass Butterworth filter with a 10 Hz cut-off frequency.

Figure 4.1 shows the F_G , F_L and F_{GR} signals from one TD subject aged 10.1 yrs. The signals from all trials were divided into 7 phases; (A) preload, (B) load, (C) ascend, (D) static, (E) descend, (F) unload, and (G) postload. The phases between A to D are collectively identified as 'lift', and E to F as 'deposit'. The duration of all phases t and the magnitude of the force parameters f and r , as indicated in the figure, were recorded and analysed. The descriptions of these parameters are described in Table 4.2. In addition to these time and force parameters, three task-dependent motor control measures were computed directly from these signals:

1. ISOMETRIC GRASP FORCE-LOAD FORCE SYNERGY measures the synergy between grasp force and load force, in terms of *linearity* and *monotonicity*, as introduced in Chapter 2.2. Prior to implementing the metrics, the relationship between the isometric grasp force and load force, during the load $t \in B$ and unload $t \in F$ phases was first computed from a total least square regression model for each subject and trial, with grasp force F_G as the dependent variable and load force F_L as the predictor variable in the form

$$F_G = \alpha_0 + \alpha_1 F_L + \varepsilon \quad (4.1)$$

where α_0 is the intercept, α_1 the linear slope, and ε the unexplained variance of the relationship, which were calculated using Eqn. (2.3) as described in Chapter 2.2. The linearity γ_{GL} and the monotonicity μ_{GL} of the grasp force-load force synergy, which measure the error from the grasp-load relationship and the non-intermittency of the grasp-load development, were then calculated using the Eqn. (2.7) and Eqn. (2.8) (Chapter 2.2), respectively.

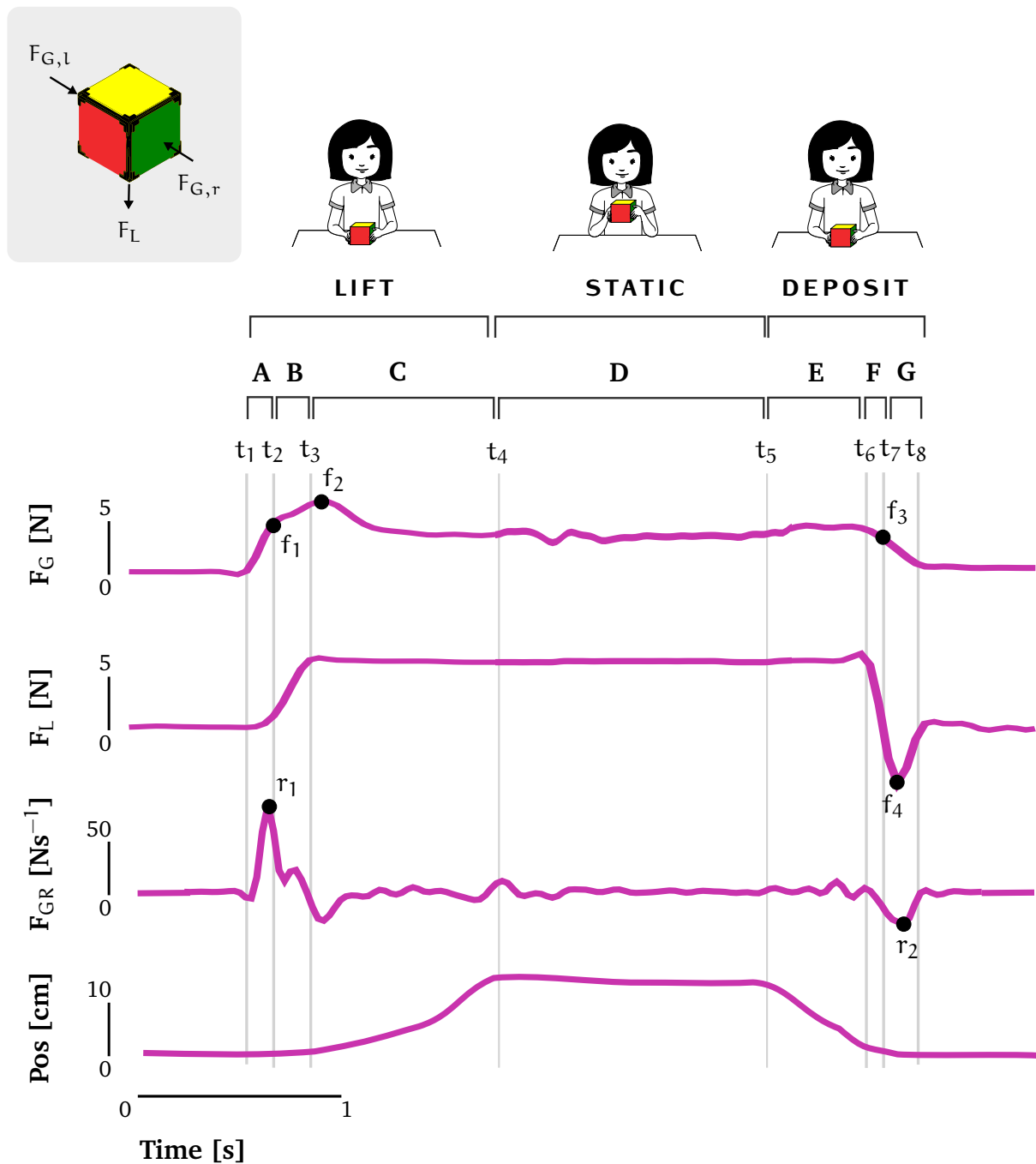


Figure 4.1 | The example of grasp force F_G , load force F_L , grasp force rate F_{GR} and position (pos) signals plotted as a function of time, from one TD subject aged 10.1 yrs. The time (t) and force (f and r) events are described in Table 4.2. Shown is division of the subject's data into 7 phases; (A) preload, (B) load, (C) ascend, (D) static, (E) descend, (F) unload, and (G) postload. The preload phase starts at the onset of $F_G > 0.2$ N, t_1 , and continues until the onset of the Cube's lift off, t_2 , marked by $F_L > 0.2$ N. During the load phase, F_G and F_L increase isometrically until the Cube is fully lifted, t_3 , where F_L reads the weight of the Cube, 5.1 N. The Cube then begins to ascend, remains static for 2 seconds and descends. The unload phase begins when the bottom face of the Cube touches the table again at t_6 , and $F_L < 5.1$ N. F_G , together with F_L , continue to decrease isometrically throughout the unload phase. The Cube is fully deposited on the table at the onset of postload phase, t_7 , where $F_L < 0.2$ N. The phase ends when both hands are fully released from the Cube at t_8 , where $F_G < 0.2$ N.

2. INTERLIMB FORCE ASYMMETRY measures the symmetry of forces produced by the preferred and non-preferred hands during lift $t \in [A : C]$ and deposit $t \in [E : G]$. The interlimb asymmetry was computed using a linear mixed-effects model, with the bias in grasp force between the preferred and the non-preferred hands $\mathbf{F}_B$ as the dependent variable and the total force from the two hands $\mathbf{F}_T$ as the predictor, in the form

$$\mathbf{F}_B = \beta_{0,s} + \beta_{1,s}\mathbf{F}_T + \varepsilon_s \quad (4.2)$$

where $\beta_{0,s}$ is the intercept, $\beta_{1,s}$ the linear slope, and ε_s the unexplained variance of the total force, which vary independently for each subject s . For each subject, $\mathbf{F}_B$ and $\mathbf{F}_T$ were normalised to their maximum grasp force. The interlimb force asymmetry for USCP group and TD group were then compared by adding the group factor $\mathbf{G}$ in the model,

$$\mathbf{F}_B = \beta_{0,s} + \beta_{1,s}\mathbf{F}_T + \beta_{2,s}\mathbf{F}_T\mathbf{G} + \beta_{3,s}\mathbf{G} + \varepsilon_s \quad (4.3)$$

which was assumed to affect the linear slope and the intercept of the force symmetry line. A likelihood ratio test was computed to determine the difference between Eqn. (4.2) and (4.3). For TD subjects, the dominant hand was assumed as the preferred hand, while for subjects with USCP, the non-affected hand was assumed as preferred hand.

3. THE SMOOTHNESS OF MOVEMENTS measured using the SPARC metric (Balasubramanian *et al.*, 2015), which quantifies the movement smoothness by measuring the signal's spectral arc length. For this study, the metric was computed on the angular velocity data during ascend phase $t \in C$ and descend phase $t \in D$.

Table 4.2 | Description of time (t) and force (f and r) parameters shown in Figure 4.1.

Parameters	Description
Time Parameters	
t_1	Onset of $\mathbf{F}_G > 0.2$ N
t_2	Onset of loading, $\mathbf{F}_L > 0.2$ N
t_3	Time when the Cube is fully lifted off the table, $\mathbf{F}_L > 5.1$ N
t_4	Onset of static phase, the Cube stops moving upward
t_5	Onset of descend, the Cube starts moving downward
t_6	Time when the Cube first touches the table, $\mathbf{F}_L < 5.1$ N
t_7	Time when the Cube is fully unloaded on the table, $\mathbf{F}_L < 0.2$ N
t_8	Time when grasp force is fully released, $\mathbf{F}_G < 0.2$ N
Force Parameters	
f_1	Grasp force at the onset of load phase [N]
f_2	Peak grasp force [N]
f_3	Grasp force at the onset of postload phase [N]
f_4	Reversed force during unloading [N]
r_1	Peak grasp force rate during applying grasp [Ns^{-1}]
r_2	Minimum grasp force rate during releasing grasp [Ns^{-1}]

The median score of each variable was chosen as a representative measure to minimise the influence of outliers and ensure the robustness of the statistical tests. Due to the relatively small sample size and the non-Gaussian distribution of the variables of interest, two non-parametric statistical tests were used: (1) a Mann-Whitney U test, to determine the significant differences between two independent groups, i.e. TD and USCP groups, and (2) a Wilcoxon signed-rank test, to determine statistical differences between two paired samples, i.e. the lifting and releasing movements, as well as between the first and the last trials of each subject. Statistical differences were calculated at 95% confidence level.

4.3 RESULTS

Table 4.3 shows the results (median $\pm$ interquartile range) from the time, force, and kinematics coordination analysis for TD and USCP subjects.

Table 4.3 | The scores for TD and USCP subjects during the lifting task. Shown are the median $\pm$ interquartile range of phase duration and force magnitude, as well as the linearity, monotonicity and smoothness scores.

Performance measure	TD (n = 17)	USCP (n = 15)
Phase duration [s]		
Preload phase	0.04 $\pm$ 0.02	0.11 $\pm$ 0.19
Load phase	0.15 $\pm$ 0.04	0.60 $\pm$ 0.64
Unload phase	0.20 $\pm$ 0.05	0.85 $\pm$ 1.00
Postload phase	0.02 $\pm$ 0.05	0.54 $\pm$ 1.22
Force, f [N] and force rate, r [Ns ⁻¹]		
f ₁	1.07 $\pm$ 0.61	1.21 $\pm$ 2.01
f ₂	5.93 $\pm$ 1.40	9.52 $\pm$ 4.35
f ₃	3.89 $\pm$ 1.17	5.97 $\pm$ 2.91
f ₄	-0.16 $\pm$ 0.34	-1.38 $\pm$ 3.18
r ₁	49.80 $\pm$ 29.24	35.64 $\pm$ 30.09
r ₂	-28.57 $\pm$ 11.34	-20.07 $\pm$ 19.67
Linearity [γ_{GL}]		
Load phase	-0.02 $\pm$ 0.01	-0.05 $\pm$ 0.05
Unload phase	-0.11 $\pm$ 0.07	-0.08 $\pm$ 0.10
Monotonicity [μ_{GL}]		
Load phase	1.00 $\pm$ 0.00	0.82 $\pm$ 0.29
Unload phase	0.82 $\pm$ 0.30	0.57 $\pm$ 0.50
Smoothness of movement [SPARC]		
Ascend phase	-5.99 $\pm$ 2.66	-16.37 $\pm$ 0.24
Descend phase	-5.08 $\pm$ 2.78	-26.75 $\pm$ 37.55

FORCE COORDINATION AND TIMING Figure 4.2 shows the duration of each phase and the force magnitude for TD and USCP subjects. A Mann-Whitney U test revealed no significant difference in the duration of the preload phase between TD and USCP subjects. The load phase duration of subjects with USCP was approximately four times longer than TD subjects, and the latency was even longer during the unload and postload phases. No significant difference in the amount of grasp force at the onset of the Cube's lift off f_1 , and the peak grasp force rate r_1 between TD and USCP subjects. However, subjects with USCP exhibited greater grasp force during lifting f_2 and at the onset of unloading f_3 , as well as slower rate of grasp release r_2 than TD subjects. The negative load force f_4 , which suggests the Cube being pressed against the table during unloading, was greater amongst subjects with USCP.

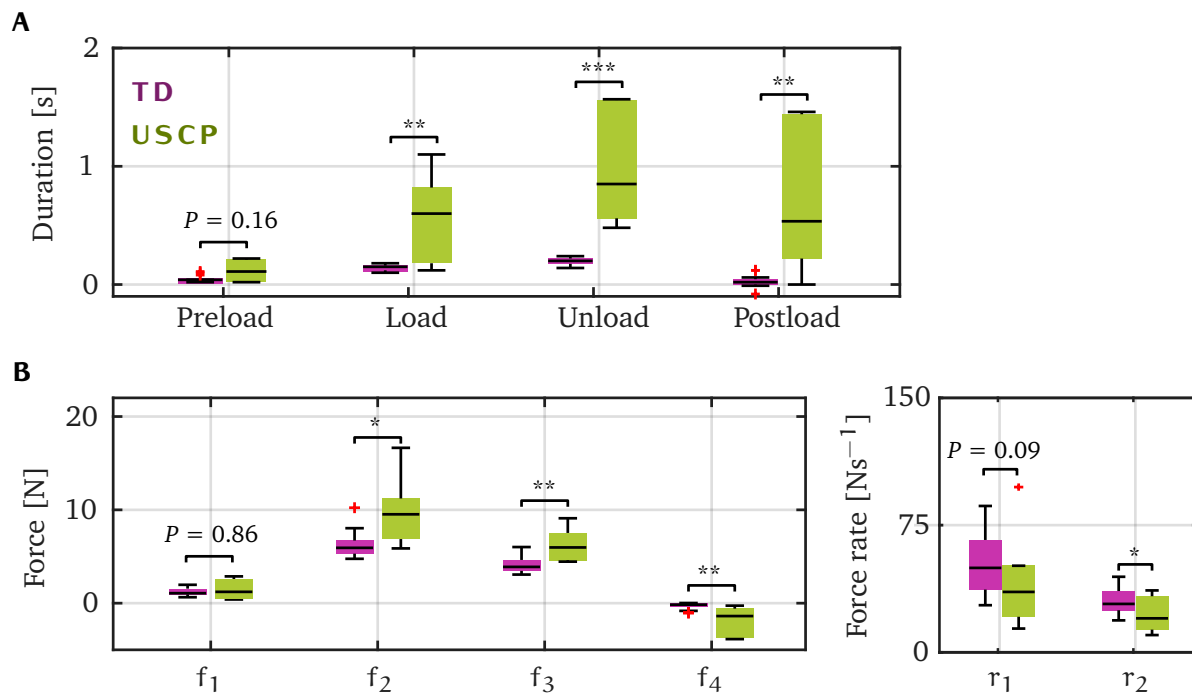
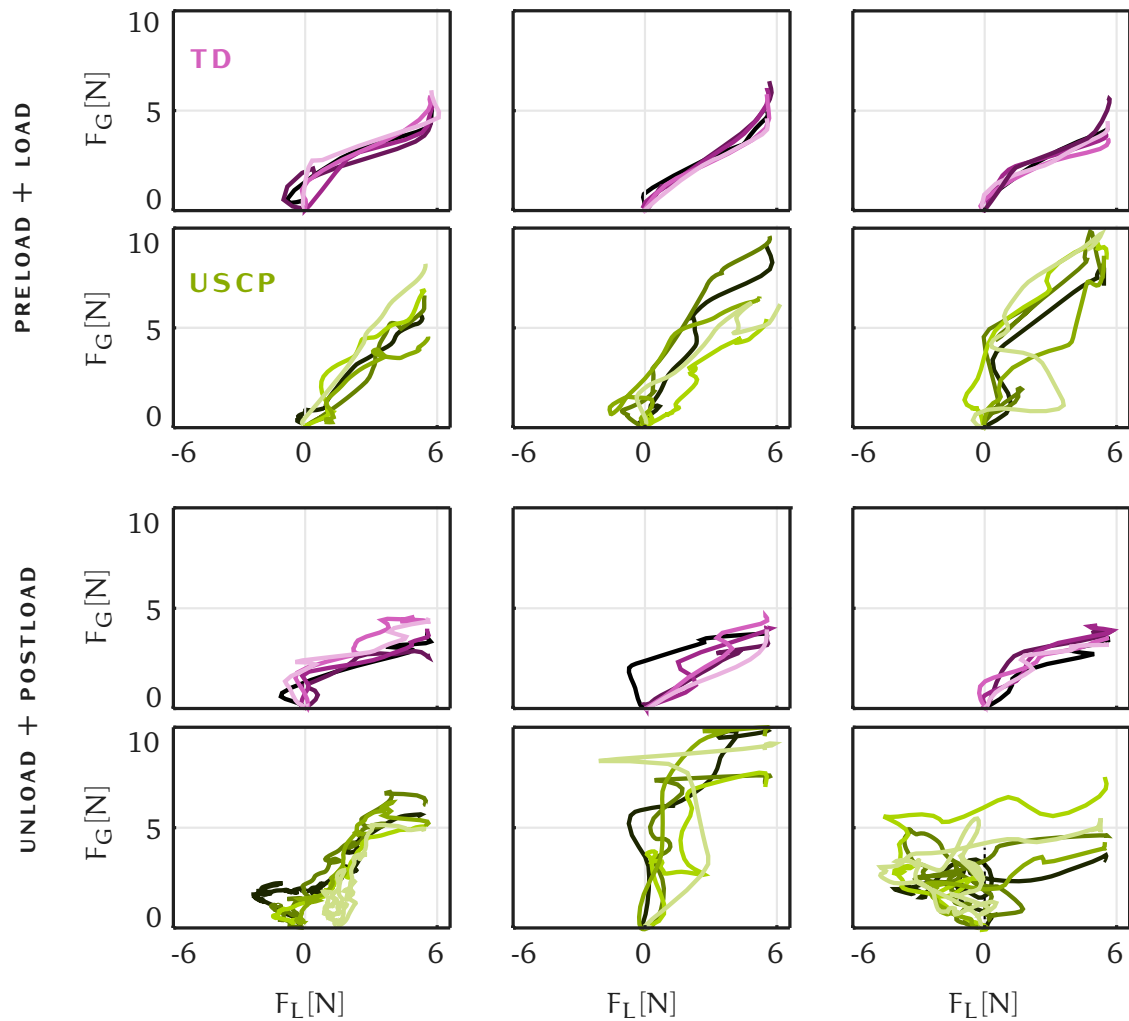


Figure 4.2 | Timing and force parameters. Shown are **A.** the duration of the temporal phases and **B.** the magnitude of the force parameters (see Fig. 4.1 for the definition of each temporal and force parameter). Box-whisker plots showing medians (line), quartiles (boxes), and minimum and maximum values (whiskers). *** represents $P < 0.001$, ** $P < 0.01$ and $P < 0.05$.

THE LINEARITY AND MONOTONICITY OF GRASP-LOAD SYNERGY Figure 4.3 shows the isometric grasp force signal plotted against the load force signal during the preload + load phases, and the unload + postload phases. TD subjects demonstrated a consistent increase in grasp and load forces during the load and unload phases, with a small variation in isometric force development between subsequent lifts. The load phase was preceded by a short preload phase, during which the grasp force increased, sometimes in conjunction with a small negative load force, when the Cube was pressed down against the table.

A GRASP-LOAD FORCE COORDINATION



B LINEARITY AND MONOTONICITY SCORES

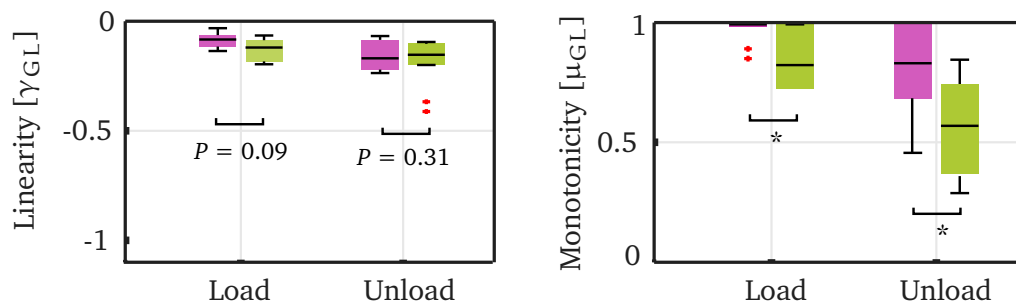


Figure 4.3 | The grasp-load force synergies during the lift and deposit phases. **A.** Shows the grasp force F_G and load force F_L signals during the preload + load phases, $t \in [A : B]$, and the unload + postload phases, $t \in [F : G]$. Five trials were superimposed for three TD subjects and three subjects with USCP. The $F_L < 0$ N area represents the frames when the Cube pressed downward against the table. **B.** Shows the linearity and monotonicity scores during load $t \in B$ and unload $t \in F$ phases.

A Mann-Whitney U test revealed that the linearity scores for subjects with USCP remained indifferent from TD subjects during the load and unload phases. However, the monotonicity scores for subjects with USCP were significantly lower than TD subjects during the load and unload phases. A Wilcoxon signed-rank test revealed no significant improvement in the linearity and monotonicity scores of the grasp force-load force synergies between the first and the last trials for both TD and USCP groups.

SMOOTHNESS OF MOVEMENT Figure 4.4 shows the SPARC scores for both TD and USCP subjects during the ascending and descending movements of the Cube. subjects with USCP exhibited lower SPARC scores than TD subjects during both movements.

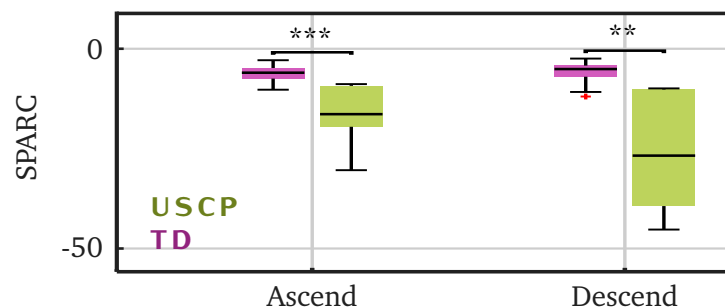


Figure 4.4 | **The SPARC scores during the ascend and descend movements of the Cube.** SPARC metric quantifies the smoothness of a movement by measuring the length of the frequency spectrum of a signal. A higher SPARC score represents a smoother movement.

LIFTING VS RELEASING MOVEMENT It is observable from the data in Table 4.3 that both TD and USCP subjects encountered more difficulties to perform releasing movement than lifting movement. With regards to temporal coordination, both TD and USCP subjects took roughly 25% longer time to release grasp than to increase grasp, which was measured from the duration of load vs. unload phases, respectively ($P < 0.01$ for TD; $P = 0.06$ for USCP). Furthermore, TD subjects took twice shorter time to fully release the grasp and complete the postload phase than to prepare grasp during the preload phase, while subjects with USCP took 80% longer time during the postload phase than they did during the preload phase, albeit not significant ($P = 0.15$ for TD; $P = 0.09$ for USCP).

The grasp-load synergies were less linear and less monotonic during unloading than during loading for TD subjects ($P < 0.001$ for linearity; $P < 0.01$ for monotonicity). In contrast, no similar difference was observed in subjects with USCP ($P = 16$ for linearity; $P = 0.09$ for monotonicity). No difference was observed between the smoothness of ascend and descend movements for both groups ($P = 0.41$ for TD; $P = 0.09$ for USCP).

INTERLIMB FORCE ASYMMETRY Figure 4.5 show the result from the linear mixed effect model of the force bias between the preferred and the non-preferred hands as a function of the total force from both hands during the lift and deposit phases. Overall, TD and USCP subjects showed bias towards the preferred hand during lift and deposit. A maximum likelihood test revealed a significant influence of USCP on the interlimb force asymmetry line ($\chi^2(2) = 5.71$; $P < 0.05$), where subjects with USCP exhibited lower intercept by 0.06 ± 0.04 N and higher linear slope by 0.06 ± 0.03 relative to TD group. The lower intercept by subjects with USCP at the beginning of the lift highlights the hand that initiated the grasping, i.e. the preferred hand, causing the Cube to fall on the non-preferred hand within the first few seconds of the lift. Similarly, there was a significant influence of USCP on the interlimb force asymmetry line during the deposit phase ($\chi^2(2) = 14.80$; $P < 0.001$), in which subjects with USCP increased the linear slope by 0.09 ± 0.05 relative to that produced by TD subjects.

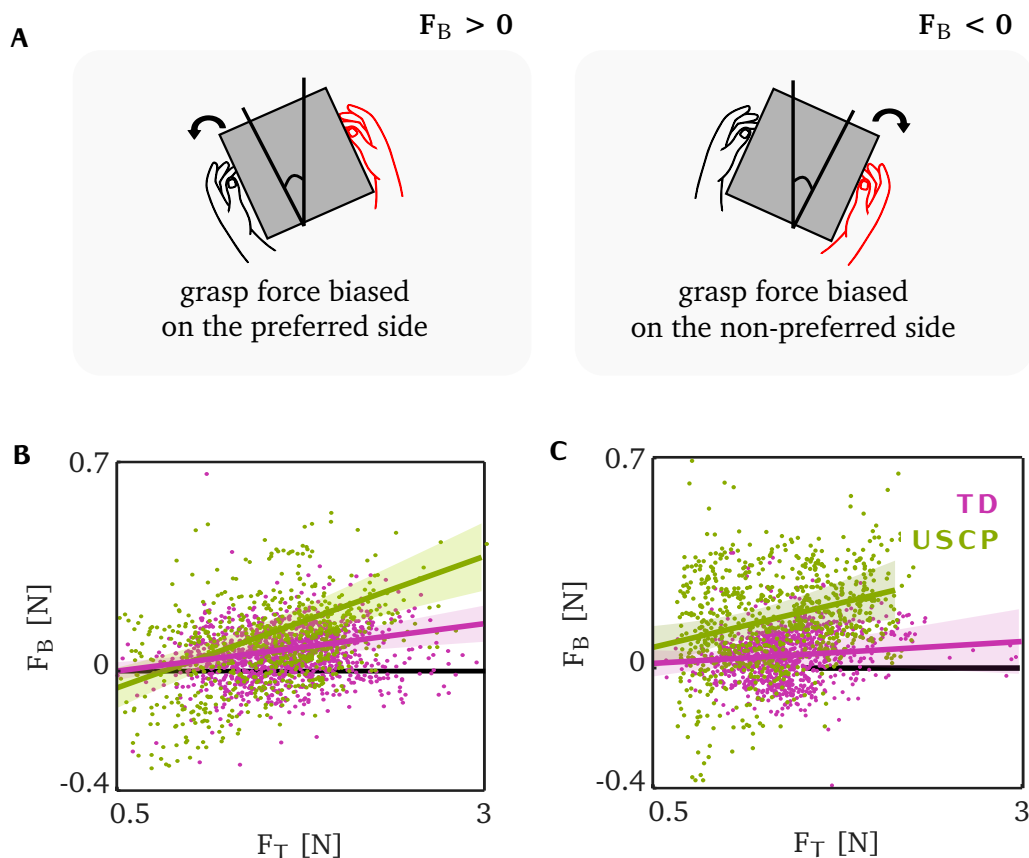


Figure 4.5 | Interlimb force asymmetry during lift and deposit phases. Shown are **A.** Illustration of the effect of Cube's rotation on the force bias magnitude, **B.** Force bias F_B as a function of total force F_T for TD and USCP group during lift phase, $t \in [A : C]$ and **C.** deposit phase $t \in [E : G]$. The shaded region represents the 95% confidence interval of the linear mixed-effects model fit.

4.4 DISCUSSION

Previous research has discussed the efficacy of bimanual tasks in improving upper limb coordination of children with USCP, as the non-affected side could act as a ‘template’ to assist the movement of the affected side (Gordon *et al.*, 2006a). For instance, a number of studies reported improved anticipation and force control of the affected side during a bimanual task, compared to an equivalent unimanual task (Gordon *et al.*, 1999; Gordon *et al.*, 2006a; Steenbergen *et al.*, 2008), although some noted that this improvement occurred at a temporal cost, where the non-affected hand slowed down to match the affected hand (Steenbergen *et al.*, 2000; Steenbergen *et al.*, 2008). However, the scope of these studies only covered the coordination of the upper limbs during a bimanual task that involves manipulating separate objects on each hand. The present experiment investigated the potential of haptic feedback, by analysing the bimanual coordination during a haptically (i.e. mechanically)-coupled task where both hands are constrained to interact with a single object, in both TD children, as well as children with USCP.

The quantification of the grasp force-load force synergy is a simple but powerful method to analyse the adaptation of grasp forces to environmental demands (Johansson, 1991). Such demands include the weight and size of an object and the friction between the object’s surface and skin. In order to produce smooth and dexterous prehension, the development of isometric grasp and load forces must be scaled to match the object’s weight (Westling & Johansson, 1984). TD children normally use a strategy which harmonises the isometric grasp and load forces by automatically adjusting to the object properties, producing a coordinated or linear grasp-load force output (Forssberg *et al.*, 1991). Conversely, children with CP usually exhibit a significantly more non-linear synergy compared to TD children during a unimanual grip task. Such behaviour can be attributed to multiple factors, such as inefficient sensorimotor integration and deficits in anticipatory control (Eliasson *et al.*, 1991; Forssberg, 1999). However, the results from the present study could not endorse the findings from these studies, as it was found that the linearity of the grasp force-load force relationship by subjects with USCP falls within the normal TD range, potentially suggesting that the subjects with USCP could linearly generate grasp force when performing the present haptically-coupled task.

Such findings may be explained by the fundamental principles that govern grasp force control. Proper control of grasp force relies on intact sensorimotor integration, as it provides the nervous system with information about the object’s physical properties (Johansson, 1991). This information allows for anticipatory scaling of the grasp force level to adjust subsequent prehension. However, children with USCP often exhibit impaired sensory function (Krumlinde-Sundholm & Eliasson, 2007), thus affecting their anticipatory control. To com-

pensate, children with USCP rely on external sensory feedback for grasping, which means the grasp force will increase excessively to amplify the sensory feedback before the object's lift off (i.e. f_1) (Eliasson *et al.*, 1991). This excessive grasp force may reflect a compensatory strategy to excite additional tactile mechanoreceptors, by increasing the skin-object contact surface. Such a strategy often leads to prolonged preload duration to permit preparation for the lifting phase (Eliasson *et al.*, 1991). However, this study found neither excessive f_1 grasp force magnitude nor prolonged preload duration during lifting in the USCP group, and their peak grasp force rate r_1 was also within the normal TD range. The findings highlight no evidence for impaired anticipation (cf. Steenbergen *et al.*, 2008), where the affected hand could produce a finer and better scaling of force control. Potentially, children with USCP were able to develop clear internal representations of the object's properties within only 5 practice trials, compared to at least 20-25 trials needed during a unimanual lift using their affected hand (cf. Gordon & Duff, 1999). Alternatively, this absence of signs of impaired anticipatory control and the linear grasp-load force synergy could also be an indication of adequate sensory information acquired from the physical coupling of the hands during the manipulation of a single object. This information could have allowed unambiguous directional cues of cutaneous and kinaesthetic information to relay between the affected and healthy limbs, thus accelerating anticipation and facilitating grasp force adaptation.

The measure of monotonicity is a metric introduced in this thesis to provide further analysis of the grasp-load force synergy. In contrast to linearity, which measures the performance error from the grasp-load relationship, the measure of monotonicity elucidates the efficiency of voluntary control of isometric muscle contractions when initiating and terminating a movement. A monotonic grasp-load force relationship involves a gradual contraction and relaxation of muscles with precise coordination of agonistic and antagonistic muscles. The results from the present study suggest that children with USCP have difficulty generating isometric grasp force patterns in a monotonic manner, evidenced by the frequent grasp-ungrasp oscillations during the load and unload phases. It has been established before that muscle weakness is one of the major problems that present in many CP cases (Brown *et al.*, 1987) — and the oscillating grasp force patterns discovered amongst subjects with USCP here could be a result of increased muscle noise that occurs due to decreased muscle strength (Hamilton *et al.*, 2004). The weak muscle prominent in subjects with USCP may have contributed to the decrease in overall smoothness of the movement itself, as it is discovered that these children produced a jerky and unsteady movement during object lift and deposit. However, the results from the analysis of interlimb symmetry show the strategy taken by children with USCP to compensate for their weak muscle, where the asymmetric distribution of grasp force during lift and deposit phases suggests that these children shifted some of the Cube's weight onto the more abled side, in order to reduce the load on the affected side. This finding

is in agreement with the results of von Walden *et al.* (2017), who found an impaired ability to control force direction amongst children with spastic CP. To compensate for their weak, thin and stiff forearm flexor muscles, these children resort to their less affected side to increase joint stability, thus creating a bias in force magnitude between the two hands.

The current experiment provides new evidence towards the understanding of impaired bimanual function amongst children with USCP. It has been previously highlighted that executing bimanual tasks will activate the intact brain hemisphere, enabling neural crosstalk at different levels of the central nervous system (Swinnen, 2002; Carson, 2005; Sleimen-Malkoun *et al.*, 2011). The present findings show that the haptic coupling of the two hands provided through manipulating a single, shared object could facilitate normal anticipation and sequencing of grasp force control. Such facilitation could potentially be due to the notable capacity of the task in providing natural cutaneous and kinaesthetic information onto the affected side, through the dynamic exchange of forces between the two hands that relay through the shared object. Furthermore, given that most children with USCP have ‘grown-accustomed’ to using only one hand during ADLs, by physically enforcing both hands to work together in a natural way, such a task could provide a simple method for encouraging the simultaneous use of both hands, besides increasing the functional capacity of the affected limb.

However, the present study only tested the haptic capacity during bimanually manipulating the rigid Cube. As such, it is unknown whether the uncovered benefits of performing a haptically-coupled task will retain even when manipulating a soft object, such as when removing jelly off its mould — where the stiffness of coupling and interaction forces between the two hands are weak. Therefore, the next chapter explores the influence of connection stiffness between the two hands on bimanual coordination, and investigate how humans modulate their performance to compensate for the decreased coupling stiffness.

5 | INFLUENCE OF SHARED OBJECT MECHANICS ON BIMANUAL COORDINATION

The previous chapter has shown how bimanually manipulating a shared object in a ‘haptically-coupled task’ can facilitate anticipatory control and grasp force sequencing amongst children with USCP. These results were attributed to the continuous exchange of force information between the limbs, generated by the opposing hands when holding and manipulating an object synergistically. For children with USCP, who exhibit severe sensory deficits on their affected limb, the force feedback from the ‘good’ limb could provide cutaneous and kinaesthetic information of its movement to the contralateral affected limb. This could then foster anticipation of the object’s properties and facilitate grasp force planning to prepare for the next movement.

The present chapter extends this study by investigating in depth how healthy adult subjects manipulate soft objects with two hands. When manipulating a rigid object like the Cube, the interaction force provides unambiguous directional cues to the opposing hand. However, when manipulating a soft object such as removing jelly off its mould, one cannot rely as much on the force from the opposing hand to move the object skilfully (Takagi *et al.*, 2018). In this scenario, the amplitude of grasp forces has to be adapted more precisely so as to avoid crushing or dropping a fragile, slippery object. This observation instigates a question: how do we readily coordinate our bimanual movement while manipulating objects of different compliance?

It was shown in Srinivasan & LaMotte (1995) that cutaneous cues are insufficient for exploring objects of different compliance using an index finger; rather, both tactile and kinaesthetic (i.e. active haptic sensing) feedback are necessary. Mugge *et al.* (2009) made a similar observation during a unimanual blind experiment where subjects estimated the softness of an object. The authors demonstrated that, in order to maintain accuracy, humans use force and positional feedback to maximise their force estimation. More specifically, while exploring a soft object, humans rely more on the positional feedback from the larger object deformation

to compensate for the low force information. Conversely, with limited positional feedback (i.e. small object deformation in a rigid object), humans rely more on the force feedback to effectively estimate the object.

Currently, it is not known whether these strategies generalise to bimanual control. Bimanual movement is different from unimanual movement, as it involves controlling two systems, whose feedback can interfere due to substantive interhemispheric communication (Swinen, 2002; Carson, 2005). Therefore, the experiment in this chapter tests the effect of shared object compliance and compares the results with previous observations in unimanual operation. Furthermore, this experiment also elucidates whether the sensory information from the two hands modulated by the object's compliance could accelerate grasp adaptation. Such improvement of performance was encountered by Iyengar *et al.* (2007), who observed that grip force coordination was improved when the contralateral hand was allowed to lightly touch the object during a lifting task — suggesting that redundant sensory information from both hands could improve haptic estimates.

The knowledge gained from this investigation may be applied to children with bimanual deficits like USCP, to understand whether they can still maximally use the existing capacity of their non-affected hand to facilitate the movement of their affected hand when modulating a compliant object with both hands. Intuitively, a very compliant interaction is close to no interaction, which means the benefits of bimanual force interaction on children with USCP as observed in the previous chapter may be reduced. It is likely that when interacting through a compliant object, the bimanual coordination will either deteriorate completely, or be adjusted depending on what sensory modalities are active and available from the mechanical properties of the object.

Therefore, to understand the mechanism behind how an object's compliance alters bimanual strategy, the experiment in this chapter systematically examined how coupling stiffness affects the bimanual coordination of healthy adults. This coordination was studied in a *continuous tracking task*, where subjects followed a randomly moving target while grasping a single virtual object with four different stiffness levels: hard, medium hard, medium soft and soft, with both hands.

5.1 BIMANUAL TRACKING TASK

A bimanual tracking experiment was conducted using the Hi5 dual wrist interface (Figure 5.1), to systematically test differences in performance when bimanually interacting with objects of different *stiffness* κ between the two hands. The Hi5, as introduced in Chapter 2.1.3, is a robotic interface designed by Melendez-Calderon *et al.* (2011) to study unimanual and bimanual wrist flexion/extension movements. It can apply computer-controlled torque on the two hands and measure the motor angle, interaction torque and muscle activity during the prescribed tasks.

The experiment was approved by the Imperial College Research Ethics Committee. 20 healthy adult subjects (10 M, 10 F; 17 right-handed, measured according to the Edinburgh Handedness test) with no known musculoskeletal or neurological injuries were recruited and gave their informed consent prior to participating in the experiment.

All subjects were naïve about the experiment. As displayed in Figure 5.1, the average trajectory of the left and the right wrists was represented by a virtual rectangular-shaped box with dimensions 4 cm x 2 cm. Prior to tracking, subjects were required to exert a minimum of 0.2 Nm of torque to virtually lift the object (grasping phase). Once lifted, subjects were instructed to wait for 2.5 s before tracking a pseudo-randomly moving target, which was represented by a long cursor with trajectory

$$\theta_t = -7.75 \sin(0.12t) - 1.64 \sin(0.28t) - 9.35 \sin(0.37t) + 10.62 \sin(0.63t) \quad (5.1)$$

for 25 seconds (tracking phase). The visual position of the target was rendered every 400 ms. A trial was considered failed if subjects dropped the object while tracking.

The whole experiment contained 48 trials that were divided into 12 bins of 4 trials. Each of the four trials in one bin was associated with a different level of object stiffness κ between the hands: *hard* ($\kappa = 850 \text{ Nm}^{-1}$), *medium hard* ($\kappa = 240 \text{ Nm}^{-1}$), *medium soft* ($\kappa = 120 \text{ Nm}^{-1}$) and *soft* ($\kappa = 70 \text{ Nm}^{-1}$). The object's compliance was felt in both hands through the torque applied by the Hi5. Subjects were randomly assigned to two equal groups by a 50% dice throw. Subjects in group 1 experienced in hard-medium hard-medium soft-soft order, while subjects in group 2 experienced in the reverse order.

PROTOCOL

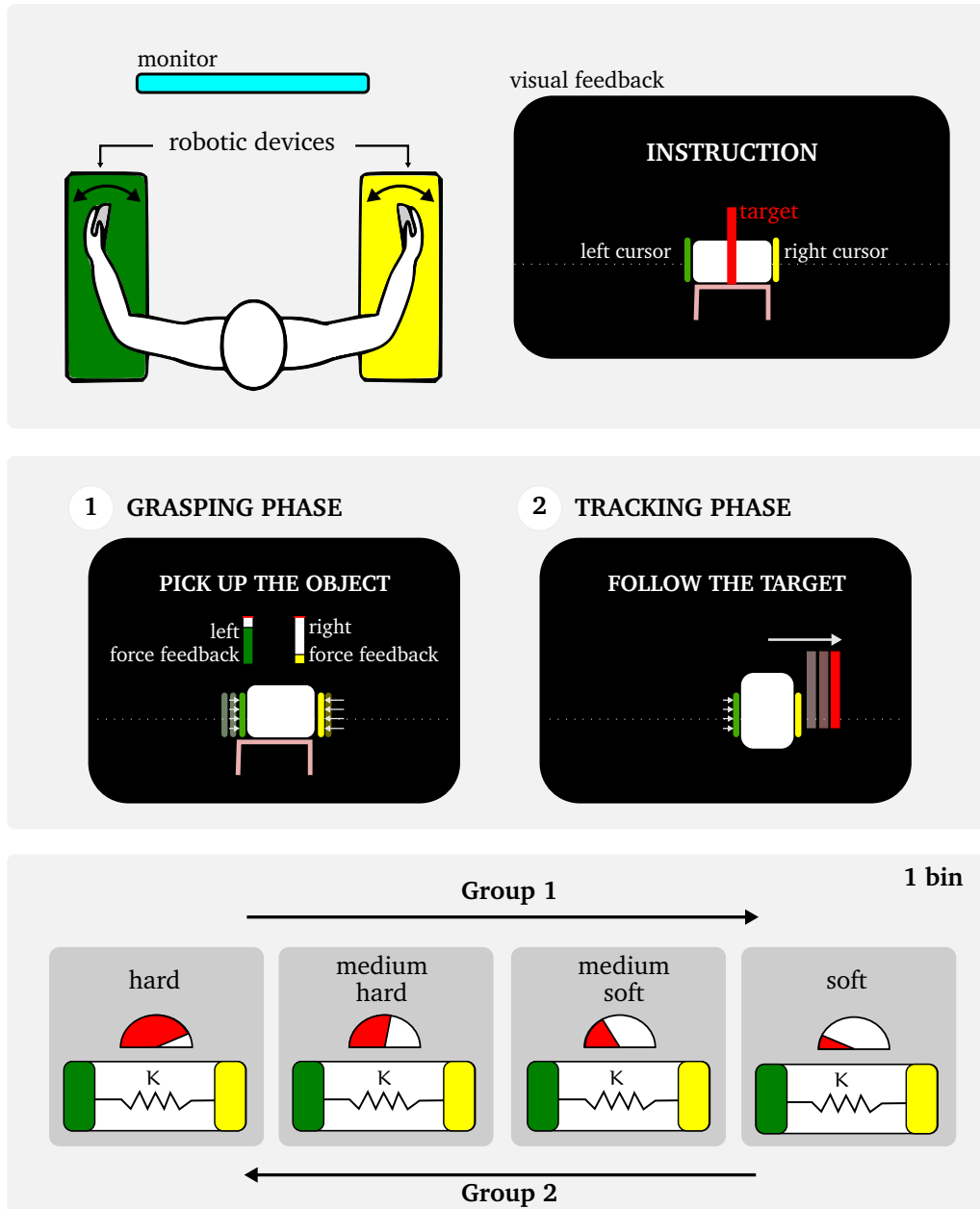


Figure 5.1 | **Investigating the influence of object stiffness on bimanual coordination.** Shown is the set-up of the dual-wrist robotic interface, Hi5, to test bimanual interaction in 1 DOF. Subjects controlled green and yellow cursors by moving their left and right wrists, respectively, to grasp an object and track a randomly moving target. The object can take four different compliance levels: *hard* ($\kappa = 850 \text{ Nm}^{-1}$), *medium hard* ($\kappa = 240 \text{ Nm}^{-1}$), *medium soft* ($\kappa = 120 \text{ Nm}^{-1}$) or *soft* ($\kappa = 70 \text{ Nm}^{-1}$).

5.2 DATA ANALYSIS

Trajectory and interaction torque data from each hand were recorded at 100 Hz using LabVIEW (National Instrument, Texas, USA). Both sets of data were forward-backward filtered using a 4th order low-pass Butterworth filter with a 10 Hz cut-off frequency. Figure 5.2 shows the mean object trajectories of every subject (coloured lines) and the target (dashed black line) at every stiffness level. The performance of each subject was measured in terms of four variables of interest:

1. **TRACKING ERROR** e_{co} measured as the root mean square difference between the target position $\mathbf{x}^c$ and object position $\mathbf{x}^o$:

$$e_{co} = \sqrt{\frac{1}{N} \sum_{t=1}^N (\mathbf{x}_t^c - \mathbf{x}_t^o)^2} \quad (5.2)$$

2. **TRACKING DELAY** δ_{co} describes the lag between the movement of the target and object. Measured from the time where the maximum significant cross-correlation between target position $\mathbf{x}^c$ and the object position $\mathbf{x}^o$ occurs.

3. **AVERAGE TORQUE** τ measured from the average torque applied by the dominant τ^D and the non-dominant τ^N hands onto the object, $\tau = (\tau^D + \tau^N)/2$.

4. **MONOTONICITY OF MOVEMENT** μ_{co} describes the non-intermittency of the object position $\mathbf{x}^o$, with respect to target position $\mathbf{x}^c$. The original ‘monotonicity’ metric as described

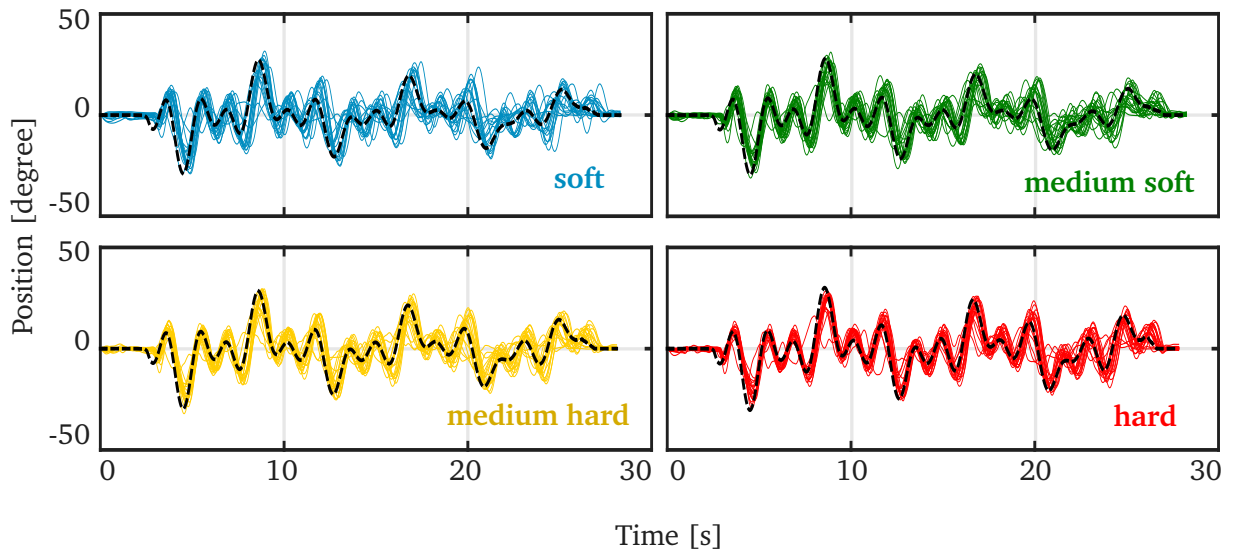


Figure 5.2 | The trajectories of the object (coloured lines) and the target (dashed black lines) at every level of object stiffness. Each coloured line represents the mean object trajectory for each subject (out of 12 repetitions).

in Chapter 2 cannot be used here, as the metric was developed for such cases where purely monotonic behaviour of the predictor variable is desired. Since the predictor variable of the current scenario, i.e. target position $\mathbf{x}^c$, is not monotonic, a new metric was thus developed to measure the monotonicity of object's movement relative to the non-monotonic target's movement, in the form

$$\mu_{co} = \frac{1}{N-1} \sum_{t=1}^{N-1} \mathbf{Q}(\mathbf{x}_t^c, \mathbf{x}_{t+\delta_{co}}^o), \quad \mathbf{Q}(\mathbf{x}_t^c, \mathbf{x}_{t+\delta_{co}}^o) = \begin{cases} 1 & \dot{\mathbf{x}}_t^c \cdot \dot{\mathbf{x}}_{t+\delta_{co}}^o \geq 0 \\ 0 & \text{otherwise} \end{cases} \quad (5.3)$$

where N is the length of $\mathbf{x}^c$ and $\mathbf{x}^o$ signals, δ_{co} is the delay between $\mathbf{x}^c$ and $\mathbf{x}^o$ (as described above), and $\dot{\mathbf{x}}^c$ and $\dot{\mathbf{x}}^o$ are the time derivatives of $\mathbf{x}^c$ and $\mathbf{x}^o$ at time t -th, respectively.

A non-parametric, paired statistical test (i.e. Friedman test) was used throughout the data analysis for testing the significant effect of compliance levels on the scores due to the relatively small sample sizes, non-Gaussian distributions of the variables of interest, and an intra-subject design. A post hoc multiple pairwise comparison test using Nemenyi's method was performed corresponding to the significant χ^2 test, to analyse performance differences between every pair of stiffness levels κ : (1) hard-medium hard, (2) hard-medium soft, (3) hard-soft, (4) medium hard-medium soft, (5) medium hard-soft, and (6) medium soft-soft.

A linear mixed effect analysis was used to investigate the influence of learning on tracking performance. This analysis was performed by constructing a model with the variables of interest $\mathbf{V}$ as a dependent variable and the number of bins $\mathbf{B}$ as a predictor variable, in the term:

$$\mathbf{V} = \beta_{0,s} + \beta_{2,s} \mathbf{B} + \epsilon_s, \quad \mathbf{V} = \{\mathbf{e}_{co}, \tau, \delta_{co}, \alpha_{co}, \dots\} \quad (5.4)$$

where $\beta_{0,s}$ is the intercept, $\beta_{1,s}$ to $\beta_{3,s}$ are the parameters for each predictor variables and ϵ_s is the unexplained variance of the variable of interests, for each subject s . The influence of the stiffness level on the degree of motor learning was analysed by adding the stiffness $\mathbf{K} = \log_{10}(\kappa)$ term, as well as the interaction term between bins $\mathbf{B}$ and stiffness $\mathbf{K}$ as predictor variables, to the model:

$$\mathbf{V} = \beta_{0,s} + \beta_{2,s} \mathbf{B} + \beta_{2,s} \mathbf{K} + \beta_{3,s} (\mathbf{B} \cdot \mathbf{K}) + \epsilon_s \quad (5.5)$$

which were assumed to affect the linear slope and the intercept of the variables of interests. A maximum likelihood ratio test was computed to determine the significant difference between Eqn. (5.4) and (5.5). The outcome of this test gives the information of how different compliance levels influence the degree of motor learning differently.

A separate test was conducted by replacing the predictor **K** in Eqn. (5.5) with a categorical variable that labelled whether the subjects were in Group 1, where they experienced hard object first, or in Group 2, where they experienced soft object first. Results revealed that the tracking error was not affected by order of the object stiffness that the subjects experienced ($\chi^2(3) = 2.53$, $P = 0.47$), therefore all data were analysed together.

Finally, a Spearman's correlation coefficient test was performed between delay δ_{co} and tracking error e_{co} to analyse the association between these two variables. Failed trials were excluded from the statistical analysis. All statistical differences were calculated at 95% confidence level, and results are reported as median $\pm$ interquartile range. Most data in this chapter are presented in the form of *violin plots*. The interpretation of a violin plot is as illustrated in Figure 3.6 (Chapter 3).

5.3 RESULTS

Table 5.1 gives the overall median $\pm$ interquartile range scores of all subjects.

Table 5.1 | Overall performance of all subjects. Shown are the median $\pm$ interquartile range scores for the four metrics (tracking error, average torque, monotonicity and delay), across all stiffness levels.

Performance measure	Soft	Medium soft	Medium hard	Hard
Tracking error [degree]	7.50 $\pm$ 1.88	6.42 $\pm$ 1.97	6.04 $\pm$ 1.65	5.76 $\pm$ 1.60
Average torque [Nm]	0.46 $\pm$ 0.10	0.51 $\pm$ 0.09	0.61 $\pm$ 0.19	0.73 $\pm$ 0.25
Delay [s]	0.14 $\pm$ 0.08	0.10 $\pm$ 0.05	0.09 $\pm$ 0.06	0.08 $\pm$ 0.04
Monotonicity [μ_{co}]	0.82 $\pm$ 0.03	0.81 $\pm$ 0.04	0.80 $\pm$ 0.05	0.80 $\pm$ 0.06

Figure 5.3 shows the influence of object stiffness and trials on the subjects' performance. Four separate Friedman tests revealed a significant influence of the stiffness level on the median scores of tracking error ($\chi^2(3) = 47.7$, $P < 0.001$), average torque ($\chi^2(3) = 60$, $P < 0.001$), delay ($\chi^2(3) = 56.32$, $P < 0.001$) and the monotonicity of movement ($\chi^2(3) = 11.58$, $P < 0.001$). A post hoc Nemenyi test demonstrated that the increase in object stiffness was associated with an increase in average torque, as well as a decrease in tracking error, delay and the monotonicity of movements (Figure 5.3A).

The effect of learning on the subject's performance was examined by comparing two nested mixed effect models as in Eqn. (5.5), one with and one without the bins **B** as a predictor variable. Maximum likelihood tests revealed a significant effect of bins on all variables of interest: the tracking error ($\chi^2(1) = 207.28$, $P < 0.001$), average torque ($\chi^2(1) =$

0.27, $P < 0.001$) and delay ($\chi^2(1) = 191.15$, $P < 0.001$), and monotonicity of movement ($\chi^2(1) = 133.07$, $P < 0.001$).

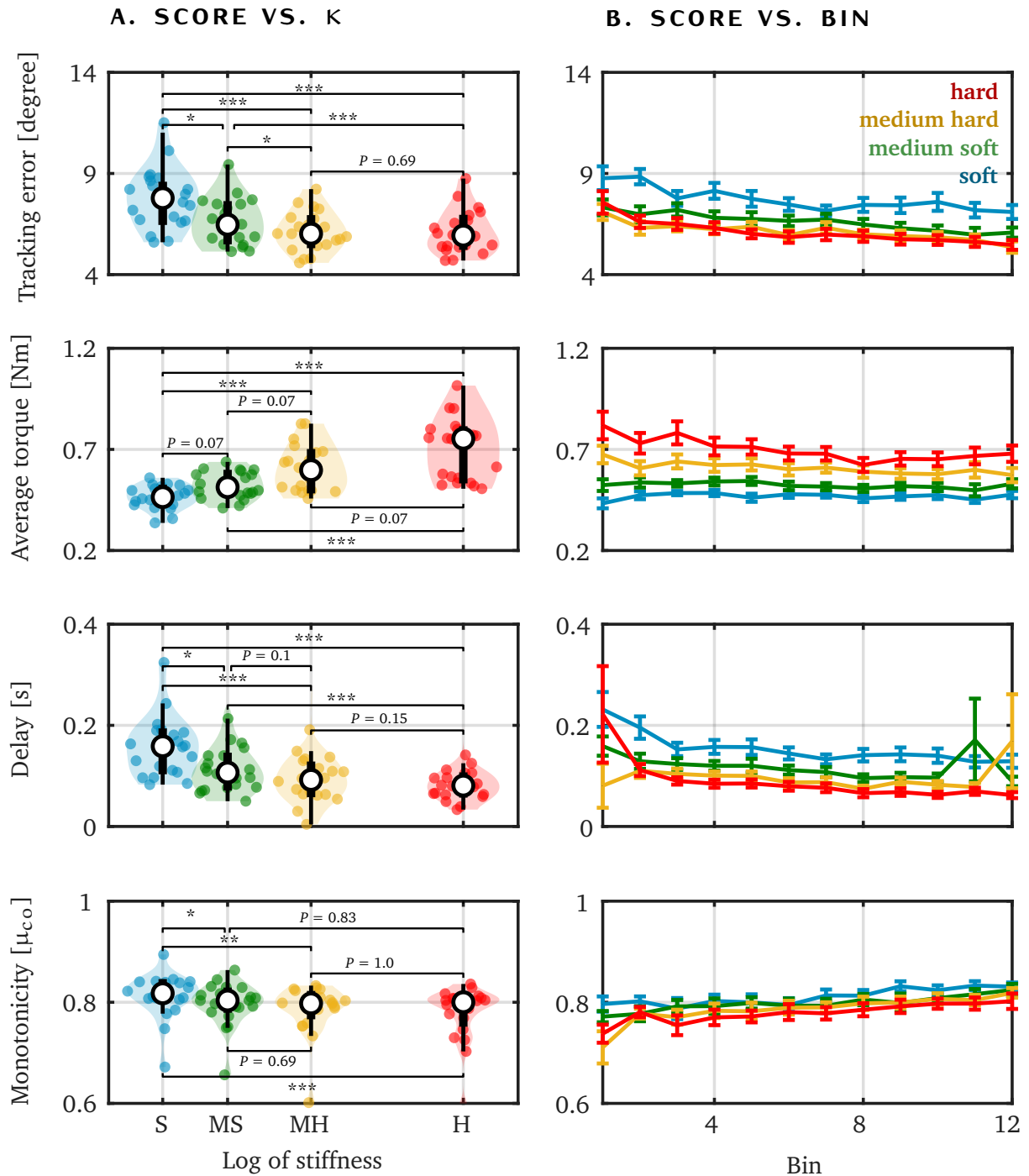


Figure 5.3 | The influence of the object stiffness K on the performance scores. Shown are **A.** the violin plots for the results from multiple comparison analysis between all pairs of object stiffness for tracking error, average torque, delay and the monotonicity of movement. **B.** the influence of learning on the scores of the variables of interest. Each line represents different level of object stiffness. *** represents $P < 0.001$, ** $P < 0.01$, * $P < 0.05$. S represents soft (blue), MS medium soft (green), MH medium hard (yellow) and H hard (red).

To analyse how the object stiffness level affects the degree of motor learning, the significance of the interaction term between the bin and log of the object stiffness ($\mathbf{B} \cdot \mathbf{K}$) in Eqn. (5.5) was measured. Maximum likelihood tests revealed that the stiffness of the objects significantly modulated the relationship between the number of bins and the average torque ($\chi^2(1) = 6.12, P < 0.01$). In contrast, the object stiffness had no effect on the relationship between the number of bins and tracking error ($\chi^2(1) = 0.05, P = 0.82$), delay ($\chi^2(1) = 0.05, P = 0.83$), the monotonicity of movement ($\chi^2(1) = 0.32, P = 0.57$) (Figure 5.3B). Collectively, these results suggest an improved performance over trials, and this improvement was generally independent of stiffness level. Specifically, the improvement occurred at the same rate for all object stiffness levels, except average torque, where the decrease in torque from the first to the last bin was only observed when modulating a hard object.

Visual observation of the data shows that the error increased synergistically with delay, suggesting that there might be an underlying association between these two variables. To verify this observation, a Spearman's correlation coefficient test was computed on the tracking error and delay. As shown in Figure 5.4A, the test revealed a strong positive correlation between these two variables of interest ($P < 0.001$ for all), implying that the tracking error is influenced by delay, which varies for each stiffness level.

To further verify this result, the root mean square error was recalculated between the target position and the corrected object position, to remove the influence of delay on the calculated error score. The corrected object position was obtained by shifting the object trajectories relative to the delay of each trial δ_{co} (see Figure 5.4B for a visual explanation). As shown in Figure 5.4C, a Mann-Whitney U test revealed that the corrected tracking error was significantly lower than the original tracking error, for every level of object stiffness. Although object's compliance continued to significantly affect the tracking error after correction to delay ($\chi^2(3) = 13.38, P = 0.004$), no significant differences were observed between most stiffness pairs, except between soft-medium soft and soft-medium hard pairs.

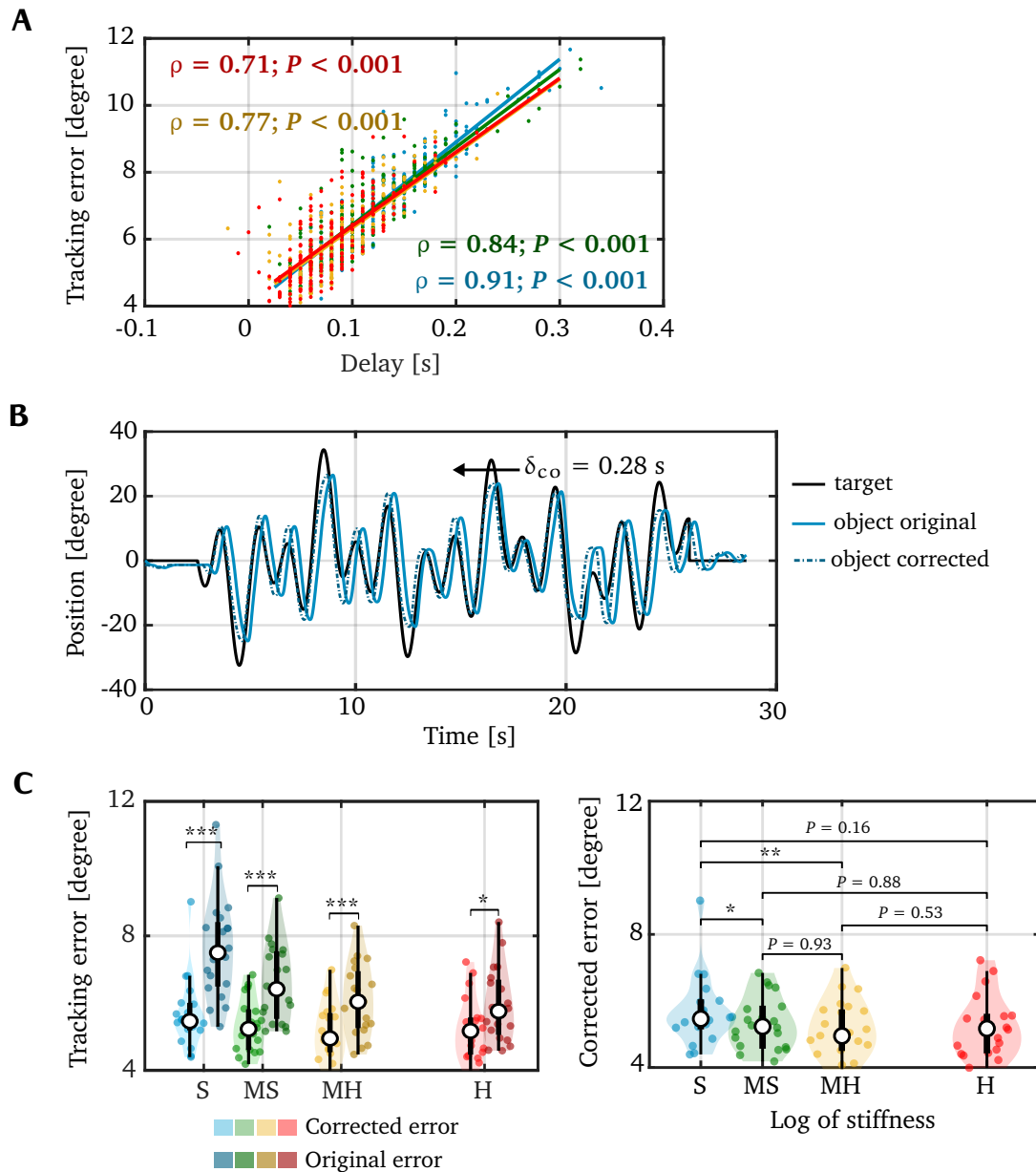


Figure 5.4 | The correlation between the tracking error e_{co} and δ_{co} . Shown are **A.** a Spearman's correlation coefficient test between the tracking error and the delay, **B.** the correction of object's trajectory based on the delay δ_{co} . Shown is an example signal from one subject in Group 1 during soft condition. **C.** Shows the comparison between the original tracking error and the corrected tracking error (left) and the comparison of corrected tracking error between every pair of stiffness levels (right).

5.4 VERIFYING THE RELATIONSHIP BETWEEN TORQUE AND STIFFNESS

An additional experiment was conducted to verify whether the observed decrease in torque with an increase in object compliance is due to the individual's performance, or the limitation of the task implementation. When grasping a highly compliant object, a larger closing displacement is required to reach a similar torque magnitude. This behaviour is as described in the spring equation $F = -\Delta x/c$, where F is force Δx is positional transformation, and c is the object's compliance.

However, as shown in Figure 5.5A, the current pseudo-random trajectory from Eqn (5.1) covers almost 80% of Hi5's margin ($\pm 34.4^\circ$ maximum amplitude). Therefore, it is possible that the smaller torque applied on softer objects is because subjects' hand movements were restrained from exerting a higher torque, as the Hi5's margin may have limited their range of wrist flexion. To examine this, the amplitude of the trajectory was decreased by 80% ($\pm 6.5^\circ$ maximum amplitude). Data was collected from 8 naïve subjects, independent of the first experiment. The results demonstrated that the torque remained higher in stiffer objects, similar to that found in the first experiment (Figure 5.5B). These findings rule out the discussed task limitation, thus verifying that the observed difference in torque is a reflection of an individual's motor performance.

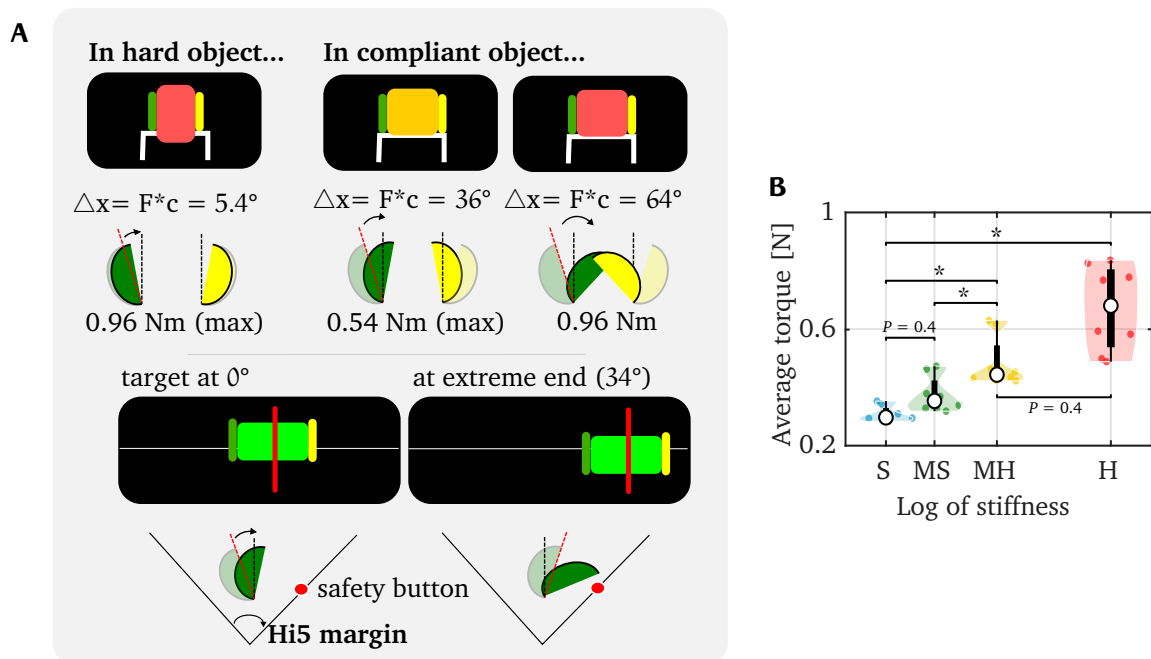


Figure 5.5 | **Verifying the relationship between torque and object stiffness.** Shown are **A.** the predicted positional transformation needed between soft and hard objects, and **B.** the results of the experiment involving the smaller trajectory.

5.5 DISCUSSION

The experiment in this chapter investigated the adaption of grasp force based on the compliance properties of an object, in healthy adults. Subjects manipulated the same virtual object through a robotic interface allowing them to experience different stiffness levels between their hands, while tracking a target using the flexion-extension of the wrists. It has been previously demonstrated that humans estimate an object's compliance in a trade-off between position and force feedback to increase their haptic estimates (Srinivasan & LaMotte, 1995). This experiment examined if the trade-off strategy is also applicable in a bimanual setting, by measuring the change in performance during an interactive two-handed task.

Together, the results lead to the following conclusions: (1) modulating softer objects with both hands results in a more monotonic movement, but at a cost of increasing performance error and delay, (2) when modulating objects of increasing compliance, humans develop a counterbalance strategy and integrate both positional and force feedback to maximise the haptic information between the two hands, and (3) the benefits of mechanically/ haptically-coupled bimanual tasks in enhancing haptic feedback between the two hands, as observed in Chapter 4, are potentially retained even with softer coupling.

The results revealed that increasing an object's compliance deteriorates the subjects' overall performance, except for their monotonicity scores, which show an improvement. Potentially, modulating a hard object could provide the subjects with a better ability to conform to the movement of their upper limbs and aim their grasp forces in a specific direction more accurately. However, a further analysis of the results shows that there was a high correlation between tracking error and delay, reflecting that the error stems from the delay in the subjects' wrist movement, likely due to the object's compliance. When grasping and moving such objects with both hands, the compliant properties of the object acts as a low-pass filter, which attenuates the force signals between the hands. This attenuation may result in a longer time to anticipate the dynamics of the opposite limb while coordinating the ongoing movement. Similarly, this low-pass filtering effect may also explain the observed smoother and more monotonic movement when modulating compliant objects. Nevertheless, with adequate practice, subjects were able to learn the strategy to minimise their performance error and delay, without jeopardising their ability to simultaneously improve the monotonicity of movement.

Despite the deteriorating performance, the results revealed an interplay between positional/kinaesthetic and force feedback when bimanually modulating objects of different compliance, similar to that found during a unimanual task (Srinivasan & LaMotte, 1995). Specifically, subjects need cues from the linear displacement of the limbs and skin when force is applied, as well as cutaneous force distribution over the skin area to properly adjust their

grasp. While some studies reported discrete switching of positional and force feedback control (e.g. Venkadesan & Valero-Cuevas, 2008), it is more likely that in the motor system, these two types of feedback are integrated and weighted *gradually*. As demonstrated in the results, when modulating the soft object, the positional cues were available, and the subjects were able to use the cutaneous force information and the surface deformation to establish a stable grasp. In contrast, with the increasingly stiffer objects, the positional cues became more limited; therefore, the subjects required a higher force to elevate the perception of pressure on their skin. This force-positional feedback integration was fashionably executed to optimise the level of haptic information between the two hands and establish a ‘just right’ grasp — so as not to exert an excessive force that can cause unnecessary muscle fatigue, or drop the object.

Notably, the high force exerted onto a hard object resembles that of individuals with sensory deficits such as stroke survivors or those with local anaesthesia in their fingers, who applied excessive grip force during precision grip (e.g. Johansson & Westling, 1984; Hermisdörfer *et al.*, 2003). The explanation for this phenomena may be similar to as previously described. The nervous system is equipped with various receptors responsible for acquiring information about movement and force. Proprioception is usually distinguished by the exteroception conveyed by the receptors in the skin, and further subserved by muscle spindles, tendon, and joint receptors. For skilled object manipulation, cutaneous receptors are of particular importance (Johansson, 1996), and any deficits in cutaneous sensation may impair one’s ability to properly adapt grip. However, even with a deficit in this function, humans are still able to utilise the force and movement signals from the muscle spindle, joint and tendon receptors to compensate for this deficit (Häger-Ross & Johansson, 1996). As such, while excessive grip force during precision grip is often interpreted as a strategic response to increase the safety margin so as to avoid slippage (Johansson & Westling, 1990), it is also likely that in this scenario, these individuals simply resort to the kinaesthetic feedback from their muscle spindles and joints to compensate for the diminished force perception between their fingers.

The mechanisms of how the brain combines haptic information from the two hands to form a unified perception may not be similar to that when using only one hand. Bimanual movements require substantive interhemispheric communication to coordinate movements of the two limbs (Swinnen, 2002; Carson, 2005), as well as more significant involvement of cortical regions such as the supplementary motor area to alter neural processing throughout the sensorimotor system (Donchin *et al.*, 1999). Therefore, only less than half of unimanual motor skills generalise to bimanual contexts (Yokoi *et al.*, 2017), due to constraints on how the brain controls unimanual and bimanual coordination (Nozaki *et al.*, 2006). However, since the results from the present study support similar conclusions as previous unimanual studies (Srinivasan & LaMotte, 1995; Mugge *et al.*, 2009), it is likely that the adaptation of the

bimanual grasp to compliance may constitute transferable motor skills between bimanual and unimanual learning. While it is still an open question as to what makes these skills transferable, one possible speculation is that, in some bimanual tasks, the difference in learning and control processes of both hands are similar enough for each hand to learn in a similar way. It is also possible that specific to this experiment, the physical coupling between the two hands could provide an optimal sensory integration of information from vision and haptic sensing (Ernst & Banks, 2002) that minimises this difference, making the strategies observed during a unimanual task generalisable to the present bimanual context. However, further study is needed to understand what makes skills transferable.

Collectively, these results suggest that the benefit of haptically-coupled bimanual tasks in enhancing sensory feedback between the two limbs, as observed in Chapter 4, may be preserved across different object stiffness levels. Specifically, humans can efficiently integrate the best available sensory modalities based on the current task demand. These findings offer a substantial advantage for children with USCP. As mentioned earlier, these children often exhibit sensory impairment on their affected side, while their non-affected side remains intact, or only has subtle sensory and motor deficit (Forssberg, 1999; Gordon *et al.*, 1999; Mutsaerts *et al.*, 2006; Steenbergen *et al.*, 1998). During a haptically-coupled task, these children can use the intact capacity of their non-affected side to perceive the force and positional information about the object's compliance, and transfer the information to the affected side through interhemispheric communication. This 'real-time' relay of positional-force feedback between the two limbs may allow them to effectively adjust their grasp and coordinate the ongoing bimanual movement, regardless of the stiffness of the object shared between the two hands. However, a further study involving the USCP population is needed to verify this hypothesis, thus establishing a need for follow-up experiments.

6 | CONCLUSION

Bimanual skill is essential in our daily lives; its significance is especially appreciated when we lose the proper use of one of our hands, such as when we break an arm. For most of us, we can regain the ability to use both hands in our ADLs. However, for children with USCP, acquiring the ability to use both hands is not as simple as recovering from a physical injury. These children exhibit severe impairment to the sensorimotor function and posture on one side of their body, that impedes the process of learning and acquiring bimanual skills.

Much of what was known in the literature about bimanual coordination in TD children, as well as children with USCP came from studies involving uncoupled bimanual tasks, where two hands manipulate two separate objects at the same time. Despite being more ubiquitous in the ADLs, little was known about how bimanual coordination develops and manifests while manipulating a single shared object, i.e. ‘physically-coupled task’. Therefore, this thesis presents four experiments that explored physically-coupled bimanual coordination in TD children, healthy adults, and most importantly, children with USCP. These experiments incorporated different forms of physical coupling (visual and haptic feedback), mechanics and congruence between the two hands.

All experiments were achieved using instrumented objects and a robotic interface, as well as novel metrics developed within this thesis that enable the quantification of various synergies between the two hands. The monotonicity metric, in particular, has shown robust performance in capturing different sensorimotor features, including the bimanual synergy and grip oscillations in Chapter 3 and grip-lift synergy in Chapter 4. The metric was extended in Chapter 5, to incorporate a non-monotonic type of signal that was not supported previously. The potential of this metric opens new capacity to quantify sensorimotor synergy between two variables, that extends beyond the usual R^2 or error metrics.

Chapter 3 began the exploration by investigating the potential of *visual feedback* in bimanual coordination. This chapter stratified the development and emergence of unimanual and visually-coupled bimanual coordination from early childhood. Indeed, the results demonstrated that both coordination refined with age in TD subjects, in a similar manner to that found in literature looking into the development of motor skills (e.g. Forssberg *et al.*, 1991;

Forssberg *et al.*, 1992). However, both TD and USCP subjects exhibited deteriorated performance during the bimanual task relative to the unimanual task. Despite no obvious influence of visual feedback on the bimanual performance of TD subjects, the results revealed the potential of using this feedback to facilitate the movement initialisation of both hands in subjects with USCP.

The second experiment in Chapter 3 investigated if and how TD and USCP subjects maintained their bimanual grip synergy when the visuomotor perception related to one of their hands was perturbed. As anticipated, the performance of TD subjects deteriorated following this perturbation. The non-impaired hand of subjects with USCP showed a similar response, but not the contralateral impaired hand, which exhibited rather noisy, and random motor patterns. These results suggest that both TD and USCP subjects were equally able to develop anticipatory control. However, for subjects with USCP, this process may be deteriorated by multilevel impairments associated with sensory input, motor output, or perhaps, everything in between (i.e. sensorimotor integration).

Chapter 4 explored the potential of natural *haptic feedback* in bimanual coordination, in a task where TD and USCP subjects lifted a single object using both hands. Similar to their TD counterparts, subjects with USCP were able to produce a linear grasp-to-load force synergy and exhibited no sign of anticipatory control deficit. These results may be due to the provision of adequate cutaneous and kinaesthetic information gathered from the dynamic exchange of forces between the two hands, that facilitates normal anticipation and sequencing of grasp force control.

Will the benefits be hampered when the haptic coupling between the two hands is weaker, such as when modulating a soft object like jelly? Fortunately, the final experiment in Chapter 5 demonstrated that the potential of haptic feedback, as observed in Chapter 4, may be retained. This experiment analysed the bimanual coordination of adult subjects when manipulating objects of different stiffness levels while tracking a moving target. The results demonstrated that, regardless of the object's stiffness, healthy adults were able to develop a counterbalance strategy that integrates both force and positional feedback to maintain an optimal level of sensory feedback. Specifically, in the cases where force feedback was limited (i.e. when modulating a soft object), subjects prioritised the positional/kinaesthetic feedback more, and vice versa, to maintain their bimanual grasp stability and continue coordinating their movement.

Collectively, the experiments in this thesis have provided a basic understanding of the bimanual coordination of TD children, as well as children with USCP, during visually- and haptically-coupled tasks. The findings from these experiments corroborate that of Contu *et al.* (2016), who found a lack of observable benefits of visual feedback in influencing the bimanual coordination of healthy adults (see Chapter 1.2.3 for a detailed review on Contu *et*

al.'s work). Instead, haptic feedback may have a more significant influence on one's bimanual coordination, as it can provide 'real-time' sensory information (i.e. force and directional cues) about the ongoing movement — which cannot be acquired through visually-coupled or uncoupled movements alone. Such additional information could accelerate anticipatory control, and facilitate better and more accurate grasp force sequencing and planning.

6.1 LIMITATIONS OF THE STUDY AND POSSIBLE FUTURE WORK

While the thesis presents critical experiments towards the understanding of physically-coupled bimanual coordination, the limitations of the study should be noted. Firstly, the study has only measured the MACS and Modified Ashworth Scale of children with USCP. Other critical clinical motor outcomes such as the Assisting Hand Assessment (AHA), which measures the bimanual capacity of children with USCP (Krumlinde-Sundholm & Eliasson, 2003), and the International Classification of Functioning, Disability, and Health (ICF), which measures their functioning and disability level (World Health Organization (WHO), 2017), were not recorded. Furthermore, their mirror movements were also not quantitatively assessed. Therefore, it was not possible to relate the bimanual performance of subjects with USCP to their bimanual hand function, or to study how mirror movement may affect their bimanual performance.

Secondly, an increasing number of studies could relate the poor bimanual function of children with USCP to the integrity of the corpus callosum and the corticospinal projection (Holmström *et al.*, 2010; Staudt *et al.*, 2002; Weinstein *et al.*, 2014). For instance, children with ipsilateral projection were shown to have the most severe hand function compared to those with contralateral or mixed projections (Staudt *et al.*, 2002; Holmström *et al.*, 2010); while children with reduced callosal integrity are more susceptible to producing mirror movements, which can influence the quality of their bimanual performance (Weinstein *et al.*, 2014). However, since this thesis did not capture such heterogeneity amongst children with USCP, the pathomechanism underlying their impaired bimanual performance cannot be understood.

Nevertheless, it is undeniable that the work presented in this thesis has only scratched the surface, and can be extended in many directions. Firstly, although the evidence for the potential of visual feedback in Chapter 3 may be inadequate, the experiment only compared hand coordination during unimanual vs. visually-coupled bimanual tasks. While it has stratified how these two types of coordination develop and differ, unimanual coordination may not provide an equivalent comparison, as it does not constitute a similar demand to that of bimanual coordination (e.g. divided attention to two separate movements). Therefore, future

study should compare bimanual coordination, with and without visual coupling, to capture the true influence of visual coupling in modifying one's sensorimotor, cognitive and visual functions involved during a bimanual interaction.

Secondly, the experiment in Chapter 5 only provided a fundamental study involving healthy adults. Future work should incorporate both TD and USCP children to investigate whether these children will demonstrate similar performance/behaviours. This information is vital to verify whether the observed benefits of haptic feedback for children with USCP will be retained even when modulating a soft and compliant object.

The final concern that the author could not fail to notice is that there is a striking lack of studies looking into the so-called 'non-affected' side of children with USCP. The non-affected side may have been assumed to exhibit normal capability or subtle deficits. However, the results from Chapter 3 demonstrated otherwise. These findings attest to the need for more studies to understand how sensorimotor skills in the non-affected hand of children with USCP develop and manifest, for example, by using the well-known precision grip protocol (e.g. Johansson & Westling, 1990; Forssberg *et al.*, 1991; Forssberg *et al.*, 1992). This will provide researchers and therapists with a thorough understanding of the impact of sensorimotor impairment on the day-to-day activities of children with USCP, so as to plan a suitable rehabilitation.

6.2 CLINICAL IMPLICATION OF THE STUDY

The knowledge gained from these studies prompts us to reconsider how we shape rehabilitation for children with USCP. The most important point to note is that, a significant part of rehabilitation offered to these children are focusing on their affected side alone, such as CIMT (e.g. Charles *et al.*, 2006; Taub *et al.*, 2004). However, since it was found here that their unilateral impairments do not only impede their affected side but also their non-affected side, potentially, incorporating the non-affected side into the rehabilitation is equally important as training for the affected one. Indeed, it is undeniable that there are some research findings, including the findings in Chapter 3, have established how performing task bimanually may impede their overall coordination (Steenbergen *et al.*, 2008; Islam *et al.*, 2011). However, the skills that children with USCP can acquire from coordinating their movements simultaneously could potentially encourage them to maximally utilise their *preserved* functional capacity of the non-affected hand to practice motor learning in a broader range of ADLs. Furthermore, considering the high variability of bimanual actions in our lives (e.g. as shown in Figure 1.1), practising tasks with varying levels of coupling and interdependence between the two hands could reflect the full range of bimanual requirements during ADLs.

This is especially important as it was previously found that less than half of the skills acquired during unimanual learning are transferable to a bimanual context (Nozaki *et al.*, 2006; Yokoi *et al.*, 2017; see Chapter 5 for an in-depth discussion). Furthermore, since it was shown in this study on the significance of haptic feedback for children with USCP, a therapy that incorporates manipulating a single object should be included. Besides ‘forcing use’ both affected and non-affected sides to prevent developmental disuse amongst children with USCP, it can also utilise the capacity of the non-affected hand in providing the force and kinaesthetic information pertaining the ongoing movement, which is something the affected side is less capable of doing.

More importantly, following the suggestion from Gordon (2011), the present thesis emphasises the importance of providing accurate ‘ingredients’ in rehabilitation. Specifically, the framework should include tasks involving CIMT, physically coupled and uncoupled bimanual training, as well as a broader range of activities — which are all equally crucial for a well-rounded rehabilitation.

6.3 APPLICATION OF ROBOTIC TECHNOLOGY FOR CHILDREN WITH USCP

The studies in this thesis have provided evidence for the outstanding capability of robotics devices and interfaces in quantifying normal and impaired sensorimotor functions of TD children, healthy adults and children with USCP. Indeed, technology-based rehabilitation is not new. One of the most promising systems available in the market, especially for children with USCP, is the *virtual reality* (VR). VR is a system that allows users to experience and interact with computer-generated environments through their senses, including vision and hearing. For children with USCP, VR can simulate different environments in which the type of activity, practice and feedback can be easily tailored to their needs and abilities.

While VR system has received increasing attention for its potential in assisting rehabilitation for children with USCP (e.g. Green & Wilson, 2012), this system has limited functionality, as it can only manipulate the visual or audio components of a task. However, as has been repeatedly emphasised throughout this thesis, visual feedback alone is not enough. Instead, both haptic and visual feedback are necessary for efficient motor learning. Integrating instrumented objects such as the Cube or the GripAble could be one simple method to incorporate such haptic feedback to users interacting with the virtual environments. These instrumented objects can be manipulated to give the users a ‘pseudo-haptic’ feel of the virtual object’s properties, such as surface contact geometry, smoothness, softness and temperature. An example

of manipulating this pseudo-haptic feedback can be as simple as integrating a vibration motor to the Cube and changing its surface texture to simulate the feeling of lifting a fragile, trembling kitten through VR. In the context of rehabilitation, this ‘mixed reality’ system will allow clinicians to manipulate object properties while having the freedom to design more realistic and complex tasks that cover a wide range of ADLs.

Robotic technology can also be used to provide an objective *assessment* of sensorimotor function. Many clinical outcomes are often classified into broad categories, such as mild, moderate, or severe, which are not sufficiently sensitive to the large variation in hand function observed in children with USCP. As can be seen in the results of Chapter 3 (e.g. Figure 3.10), many subjects with USCP exhibit an overlap of performance with those with higher or lower MACS level, suggesting that the measure may not be sensitive enough to capture the true sensorimotor deficit. An objective assessment can complement these clinical outcomes, to extract finer details on the severity and extent of sensorimotor impairments in children with USCP. Furthermore, sensors, such as force motion sensors can also be integrated into toys and tools used during therapy. Since it is commonly agreed that there is no ‘one-size-fits-all’ therapy, the information acquired by these sensors may allow clinicians to monitor and document patients’ progress over time, so as to tailor the treatment modalities and provide a pinpoint strategy for each of these individuals.

6.4 ASSOCIATED PRESENTATIONS AND PUBLICATION

The work in this thesis has been published or presented at:

1. Mutalib, S. A., Mace, M. & Burdet, E. Bimanual coordination during a physically coupled task in unilateral spastic cerebral palsy children. *Journal of NeuroEngineering and Rehabilitation* **16**, 1 (2019). URL: <https://doi.org/10.1186/s12984-018-0454-z>.
2. A poster presentation: "An instrumented toy for the assessment of hemiplegic cerebral palsy infants" at the 15th World Congress of International Society of Prosthetics and Orthotics 2015, Lyon (France). This poster received The Best Poster Award.
3. A poster presentation: "Are two hands better than one?: Physically coupled bimanual coordination in hemiplegic cerebral palsy children" at the International Neurorehabilitation Symposium (RehabWeek 2017), London (UK).

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APPENDICES

APPENDIX A: THE CLASSIFICATION OF CEREBRAL PALSY

A brain injury that leads to CP can occur before, during or shortly after birth, and the variation of the time of occurrence, the location of the brain injury and associated disorders organised children with CP into a very heterogenous classification systems. The most commonly used subdivision is based their *motor impairment*, observed from muscle tone or movement disorder of the affected child (Rosenbaum *et al.*, 2007). Three types of CP fall into this subdivision - spastic, dyskinetic and ataxic. *Spastic* is the most common type of CP, making up about 72% - 91% of the affected children. It occurs due to damage to the motor cortex, a part of the brain that maintains the coordination, precision and timing of a movement. Spastic CP can be characterised by hypertonia, or increased muscle tone, which almost always makes voluntary movements appear stiff and less fluid, or 'spastic'. According to Surveillance of Cerebral Palsy in Europe (SCPE), these children can be further divided into unilateral spastic, where half side of the body is affected (also related to 'hemiplegia' described in the next paragraph), and bilateral spastic, where both sides of the body are affected (McManus *et al.*, 2006). Dyskinesia results from damage to the basal ganglia of the brain. Children with dyskinesia can be associated with involuntary and uncontrollable movements, which are especially prominent when they attempt to move. Ataxia occurs due to damage to the cerebellum. Children with ataxic CP often demonstrate abnormal muscular coordination and their movements often appear clumsy and jerky (McManus *et al.*, 2006). Each type of CP within this subdivision is not exclusive, i.e. the affected individual can distinctively show 'mixed' features at a time, for example, spastic and dyskinetic (Rosenbaum *et al.*, 2007).

Another subdivision of CP is based on *anatomical distribution* of the affected limbs. It composes three different types - hemiplegia, diplegia and quadriplegia. Figure A.1 shows the representation of the affected body parts in this subdivision of CP. Hemiplegia involves motor impairment to a half side of the body, with more severe upper limbs than the lower limbs. On the other hand, diplegia, can be characterised by motor impairment of the legs, and occasionally, with limited involvement of the arms (Rosenbaum *et al.*, 2007). Children

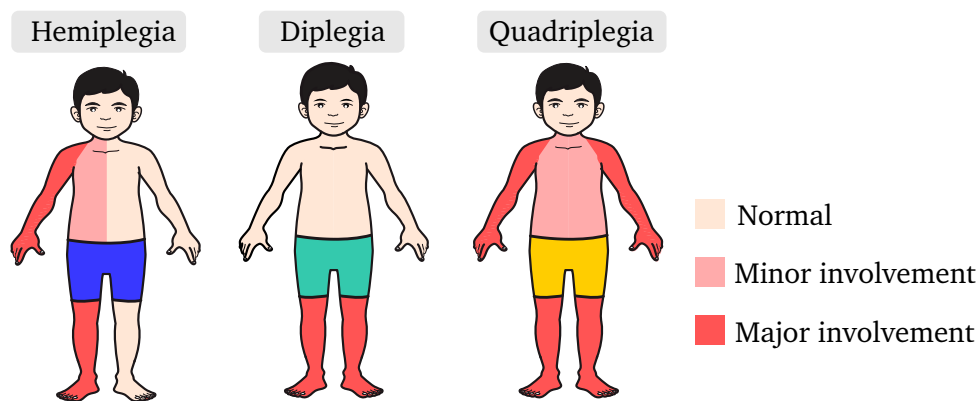


Figure A.1 | Three different types of cerebral palsy based on the anatomical distribution of impairments.

with quadriplegic form of CP primarily present with impairments to all four limbs, which consequently affect the functional capabilities of the whole body (Odding *et al.*, 2006).

In addition to these two conventional classification systems, Manual Ability Classification System (MACS) was developed as a method to systematically classify children with CP based on their motor abilities. MACS describes how children with CP use their hands to handle objects involved in ADLs, such as tools for eating, dressing, playing, drawing and writing (Eliasson *et al.*, 2006). This system is especially used among children with unilateral spastic CP, of whom evaluating their walking ability is unnecessary as most of these children often do not have a problem with mobility, while MACS focuses only on the upper limb ability of the affected children. MACS scale ranges from I - V, with level I indicating that the child handles most objects easily and successfully and level V indicating that the child has a severely limited ability to perform even easy tasks. Table A.1 shows the full description of MACS levels. In this thesis, only children with CP, diagnosed as 'unilateral spastic' according to SCPE, with MACS level I - III were recruited as parts of the inclusion criteria of the experimental group.

Table A.1 | Manual Ability Classification System (MACS) level description. Adapted from Eliasson *et al.* (2006).

MACS level	Description
Level I	Handles objects easily and successfully.
Level II	Handles most objects but with somewhat reduced quality and/or speed of achievement.
Level III	Handles objects with difficulty; needs help to prepare and/or modify activities.
Level IV	Handles a limited selection of easily managed objects in adapted situations.
Level V	Does not handle objects and has very limited ability to perform even simple actions.