Marks of conscious engagement when performing a motor task with or without a robotic arm

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Abstract

Utilizing prosthetic limbs effectively and alleviating the conscious burden through minimizing conscious control is important to address and understand in the ever-changing world of technology. Prosthetics can be difficult to learn how to use effectively and using them increases conscious awareness which is termed a burden. The conscious burden prosthetics have on users is consistently addressed by a multitude of studies and garners for more in depth research to understand and identify solutions to alleviate this burden. Conscious motor control is defined as the level of awareness of an individual performing a movement related skill or task, where the higher the conscious control the more an individual is thinking of their movements while executing them. The aim of this thesis was to measure conscious burden objectively by examining the marks of conscious engagement when performing a reaction time task with and without a robotic arm.

Chapter 1 is an introduction to this thesis including a literature review of relevant topics such as prosthetic limbs, conscious movement control, subjective and objective measurements of conscious movement control and electroencephalography (EEG). Prosthetic rejection rates, conscious burden and prosthetic limb learning are also addressed. The outline of the experiment for this thesis is included and discussed more in depth in Chapter 2.

Chapter 2 is the experiment in full examining the level of conscious control while participating in a reaction time based motor learning task using a robotic arm versus own arm. There were two conditions, the complex condition (multi-choice) and simple condition (single choice). A secondary task of tone counting was included in half the trials to examine whether more conscious processing is involved when working with the robotic arm versus normal arm while doing the reaction time task. It was expected that there would be higher conscious control and slower reaction times when participants used the robotic arm compared to their own arm.

EEG was used to assess the connectivity between the left temporal verbal-analytical (T7) site and the motor planning mid-frontal (Fz) site of the brain. Connectivity of T7-Fz is used to measure the verbal-analytical engagement in motor planning which is then used to measure conscious control. The results revealed the complex condition had a significantly higher reaction time dual-task cost for arm compared to robotic arm and a higher T7-Fz connectivity dual-cost (difference in performance for single versus dual task) for the robotic arm in the complex condition compared to simple condition. We concluded that use of a robotic arm increases verbal-analytical engagement when performing a motor task compared to using the own arm.

Chapter 3 is the overall discussion of the experimental findings for the use of robotic arms in reaction time tasks measuring conscious control and what it may mean for future research. Implicit motor learning is discussed as well as implicit motor learning interventions such as dual-task learning, analogy learning and errorless learning. There are also other learning interventions to promote intuitive control in prosthetic limb learning such as gaze training and neurofeedback.

Acknowledgment

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Chapter 1: Introduction

1.1 Prosthetics

Quality of life is one of the most important aspects of independence in an individual's perception of life and common features of quality of life include personal health (mental, physical and spiritual), relationships, work and social status, autonomy in decision making and social belonging (Koller & Lorenz, 2002). Quality of life may be impacted with the loss of a limb through amputation and in some instances being born without certain limbs. The availability of prosthetic limbs for individuals who have lost a limb is due to the advancing technology to design and construct more effective prostheses. Prosthetic rehabilitation has the potential to improve function and increase quality of life and associated with a greater likelihood of gaining employment back (Raichle et al., 2008).

1.1.1 Prevalence

According to the World Health Organisation (2005) about 3 million people have had upper-limb amputations. Within New Zealand there is estimated that around 1 in 1000 individuals have lost a limb (Peke Waihanga, Artificial Limb Service, 2024). Prevalence of upper limb prosthetic use ranges drastically (27-56%) across different studies (Raichle et al., 2008) and the prevalence of amputations in 2005 in the United States was 1.6 million with the trajectory possibly doubling by 2050 (Maduri & Akhondi, 2019). Literature relating to prosthesis use has predominantly focused on the elderly with health-related disorders such as diabetes or dyvascular disease that lead to limb loss (Dillingham, Pezzin, MacKenzie, 2002; Pezzin et al., 2004). However, trauma through accidents can also require limb amputation such as military persons in combat (Resnik et al., 2012; Winkler, 2009).

1.1.2 Types of Prosthetics

There are varying types of prosthetics depending on the intended use and functionality of them. For aesthetic purposes, cosmetic prosthetics provide a substitution for the missing body part or limb while functional prosthetics facilitate the inclusion of the missing limb for daily movement and specific activities relating to work or sport (Cordella et al., 2016). Upper-limb prosthetics can be hook or hand-shaped and are activated by the body (see Figure 1.1) or myoelectrically controlled (see Figure 1.2) (Leblanc, 1988).

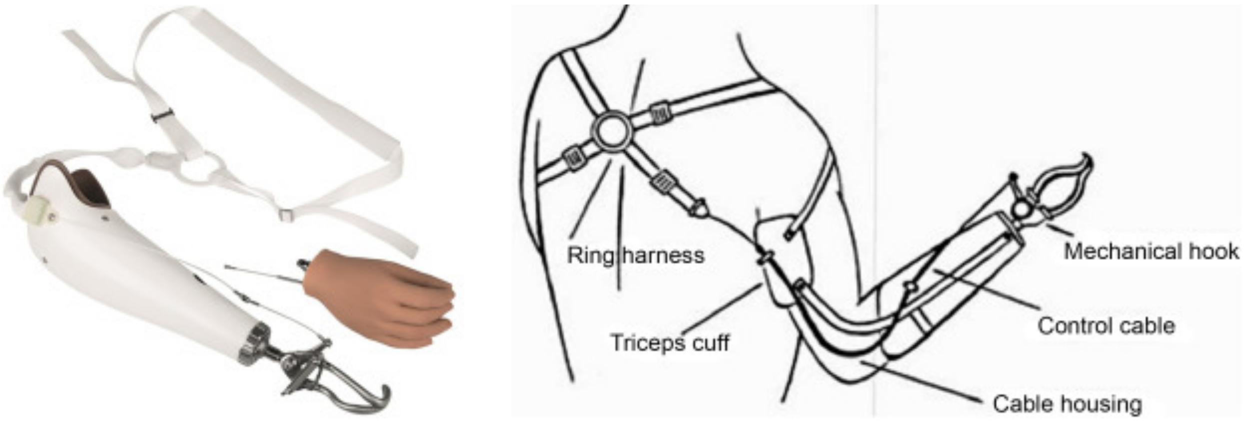

Figure 1.1. Body-powered prosthetic, either hook or hand-shaped (Beckerle et al., 2019, p. 254).

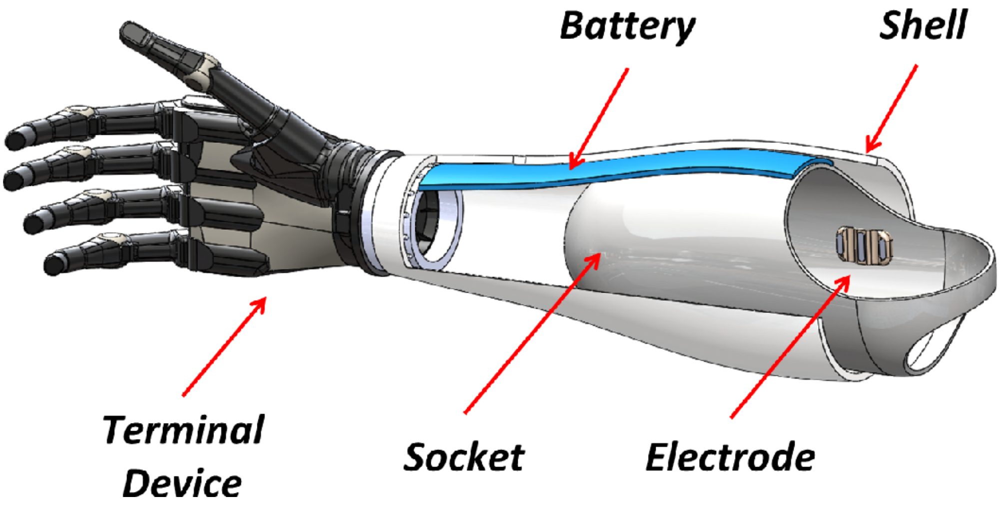

Figure 1.2. Myoelectric prosthetic (Vilarino, 2013, p. 3).

Upper-limb prosthetics activated by the body can be powered by the movements of the shoulder and arm of the intact limb via a Bowden Cable which is a small flexible cable used to transmit mechanical forces by movement such as elbow flexion and extension (Hichert, Abbink, Kyberd, & Plettenburg, 2017). Upper limb prosthetics activated by myoelectric signals are controlled by the electrical properties of muscles measured through electromyography (EMG, Chadwell et al., 2016). The EMG signals are activated by residual musculature and the electrodes pick up the signals which are in the prosthetic socket (Chadwell et al., 2016). Despite the potential to be effective with time and effort, myoelectric prosthetics are cost ineffective, less durable and more difficult to maintain compared to body-powered prostheses (Carey, Lura, & Highsmith, 2015; Parr, 2018).

Body-powered and myoelectric prostheses are equally preferred (Biddiss & Chau, 2007), dependent on the individuals use and desire to use their prosthesis in social situations or work/sport related activity (Silcox, Rooks, Vogel, & Fleming, 1993). Socially, individuals may use body powered prosthetics as they can look more like a normal hand while myoelectric prosthetics are preferred more in sport/movement related activities due to the range of functions. Successful prosthetic use has been measured by time and error in previous studies for motor performance such as Edelstein and Berger (1993) study where children with upper-limb amputation performed certain motor tasks faster with a myoelectric prothesis (putting on socks, applying a plaster) and other tasks faster with a body-powered prosthesis (playing cards) following a training period of 3 months. With increasing research and advancements in technology, there may be a switch to individuals favouring myoelectric prostheses in the future as movements can be taught effectively and intuitively (Carey, Lura, & Highsmith, 2015; Parr, 2018).

There is also the progressive production and innovation of 3D printed prostheses which provide a unique and individualized solution for users (Banga, Kalra, Belokar & Kumar, 2020). While they can be created aesthetically, which can increase user satisfaction, the 3D printed prostheses can be manufactured to adapt to everyday functions (Banga, Kalra, Belokar & Kumar, 2020). The components of a prosthetic also include socket liners made with materials such as silicone, foams and gels assist in the comfort and length of time while wearing one (O'Keeffe & Rout, 2019). Prosthetics can be specifically designed to be dynamic for sport and movement to mimic different functions like throwing or running, and carbon fibre tends to be the recommended material for such devices (O'Keeffe & Rout, 2019).

1.2 Prosthetic limb learning

The complete rehabilitation process requires ample time and effort mentally and physically while working with experienced therapists and prosthetic experts to learn how to complete daily activities using a prosthetic. Rehabilitation includes general conditioning exercises to stretch the shoulder and elbow and strengthen arm muscles as well as endurance exercises where necessary (Isaac, 2023). Specific exercise programs are prescribed depending on the individual's situation which is assessed by the nature of limb loss (acquired vs. congenital), level of limb loss, how many limbs are affected and where they are at in life (Isaac, 2023; Johnson & Mansfield, 2014). Other factors which heavily influence the rehabilitation time frame include type of prosthetic used, any previous prosthetic training or therapy, motivation of the client and experience level of the prosthetist (Johnson & Mansfield, 2014). Occupational therapists assist in helping the individual to learn how to use their prosthetic for daily activities and certified prosthetists help with the overall function and comfortability of the prosthetic as they are experienced in how prosthetics are manufactured (Johnson & Mansfield, 2014). When receiving a prosthetic, individuals are taught the initial basics of how to put the prosthetic on and off, how to move it and how to care for the prosthetic and their skin of the residual limb

(Isaac, 2023). Certain body movements are taught so the individual can contract and control specific areas of their remaining upper limbs and to maintain range of motion such as chest expansion, shoulder depression and abduction, elbow flexion and extension and forearm pronation and supination (Atkins, 1989). There are five motion elements that are primarily used in hand manipulation which are reach, grasp, move, position and release. These elements are beneficial to master before moving on to functional use training which includes movements such as opening a jar, using scissors, dressing, using tools and/or driving a car (Atkins, 1989). Rehabilitation is an ongoing process where the aim is to get people back to living a stable, independent lifestyle socially and occupationally (Atkins, 1989).

Studies have examined different training protocols such as internal and external focus of attention in relation to prosthetics. Focus and attention has been researched in relation to motor learning and performance where external focus can be placed on the outcomes of a movement like closing a prosthetic hand and internal focus is directed at the individuals body movements and feelings like contracting a certain muscle (Wulf & Prinz, 2001). There are contradictions about which attentional focus (internal or external) is more effective in learning movements with a prosthetic limb. There is an advantage of an external focus of attention in sport and human movement as it can enhance accuracy (Bell & Hardy, 2009), force production (Marchant, Greig, & Scott, 2009) and balance (Kim, Jimenez-Diaz, & Chen, 2017) however, prosthesis training promotes a predominantly internal focus of attention on specific body parts and muscles due to the nature of the movements being precise (Kristoffersen et al., 2021).

One study showed how targeted and individualized prosthetic training had a positive effect on prosthetic acceptance where the quality of the training was most important (Salminger et al., 2022). Quality of training refers to the education and experience of the prosthetist or therapist in knowledge, technology, understanding and social aspects of prosthetic use

(Spaulding, Kheng, Kapp, & Harte, 2020). There are factors which have been described as the most critical factors for prosthetic abandonment are comfort, function and weight (Kerver, van der Sluis, van Twillert, & Krabbe, 2022; Salminger et al., 2022; Schultz, Baade, & Kuiken, 2007; Smail, Neal, Wilkins, & Packham, 2021). Function-related items such as “grabbing,” “picking up,” and “speed of movements” are deemed important for prosthetic users (Kerver, van der Sluis, van Twillert, & Krabbe, 2022) and the training of these movements are vital in the rehabilitation process.

Prosthetic limb learning is an ongoing process as more studies are needed to find effective training techniques to transfer movement skills and the varying levels of experience in prosthetists and therapists all have a direct impact on the rehabilitation process (Bouwsema, van der Sluis & Bongers, 2014).

1.2.1 Rejection rate of prosthetic limbs

Although the research surrounding prostheses use and engagement is ongoing to find effective ways to teach users how to function with a prosthetic limb, a great number of individuals with amputations do not use their prostheses (e.g., Raichle et al., 2008). Prosthetic abandonment in users is high ranging from 30-50% (Witteveen, De Rond, Rietman, & Veltink, 2012) because of the lack of comfort while wearing a prosthetic, the effectiveness and time for training and the mental strain it can produce (Espinosa & Nathan-Roberts, 2019). Salminger et al. 2022, conducted a study to gather current data on prosthetic usage and found that the amount of training did not show any influence on prosthetic acceptance, and they suggested that the quality of training is a relevant factor. The longer a prosthetic device is used, the less likely it with be abandoned which attributes to the initial guidance and training delivered (Salminger et al., 2022). Although there have been continuous advancements to provide solutions for improved wearing comfort, weight and function of prosthetics, rejection rates are still high.

There are certain invasive methods such as targeted muscle reinnervation (TMR; Kuiken et al., 2007) and osseointegration (Ortiz-Catalan, Hakansson, & Branemark, 2014) that have seen to have a positive impact on device acceptance. By combining future technologies like osseointegration, implanted interfaces and prosthetic feedback, advancements in enhancing prosthetic function will be useful for individuals and hopefully increase overall acceptance.

1.2.1 The conscious burden in prosthetic limb learning

Simple everyday tasks such as "brushing teeth," "picking up a coffee mug," and "opening a door" can become complex frustrating tasks when having to learn to perform them with a prosthetic limb because of expects like relying on visual feedback (instead of proprioceptive feedback; Badawy & Alfred, 2020) and learning new patterns of muscle contractions and body movements (Childress, 1992).

When learning to control prosthetic limb, individuals are going back to the initial stage of learning, which is called the cognitive stage in the stages of learning theory by Fitts and Posner (1967). The three stages of learning are the cognitive stage, the associate stage and the autonomous stage. The cognitive stage of learning involves the processing and acquisition of new information, which requires high cognitive load. Task goals are established in this stage and used to determine the appropriate chain of movements to achieve these goals (Zhu et al., 2010). Cognitive load is defined as the number of mental resources required to process information and successfully complete a task, so a higher cognitive load means excessive use of conscious motor control (Rackerby, Lukosch, & Munro, 2022). Individuals may not progress through the stages of learning quick enough to become automatised in using the prosthetic, as prosthetic training is complex and increases fatigue, which may then increase rejection of the prosthetic. Therefore, multiple studies define the use of prosthetics as a 'conscious burden'

(Park & Zahabi, 2022; Parr et al., 2019; Rackerby, Lukosch, & Munro, 2022; Williams et al., 2006).

Conscious motor control is defined as the level of awareness of an individual performing a movement related skill or task, where the higher the conscious control the more an individual is thinking of their movements while executing them. An example of this is when a person climbs upstairs while talking, the movements are processed automatically however, automatic processing can be disrupted if the person begins to think about their exact movements like bring the knee up, flex the ankle, and lean forward. Conscious control of movement is an explicit and effortful process that involves isolating and focusing on specific movements (Masters, Polman, & Hammond, 1993). Conscious control plays an important role in motor performance where a higher level of consciousness in executing a skill reduces the autonomy of the individual which is agreed by the theory of reinvestment (Masters, 1992; Masters & Maxwell, 2008), constrained action hypothesis (Wulf & Lewthwaite, 2010), and explicit monitoring theory (Beilock, 2011). According to Baumeister (1984), "situational demands for excellent performance (i.e., pressure) cause the individual to attend consciously to his or her internal process of performance, and this consciousness disrupts that process and harms the performance" (p. 618).

Parr et al. 2019 found an increase in conscious control when participants used a prosthetic hand. They measured conscious control by electroencephalography (EEG) and eye-tracking when performing movement tasks with a robotic hand versus participant's own hand. An increased cognitive load was reported when participants used the robotic hand as EEG results showed spatial and temporal disruptions to visual attention and hand-eye coordination. Measuring conscious movement control can be subjective or objective and is discussed in the following section.

1.3 Measuring conscious movement control

1.3.1. Subjective measures of conscious movement control

There are subjective measures of conscious movement control that have been used in previous research such as secondary tasks. Secondary tasks can be used to measure whether someone is consciously involved in the motor task by measuring the conscious engagement in each task and assessing the performance outcome for the secondary task and the motor task. When working memory is engaged in the motor task there is limited capacity left for the secondary task. Performance during secondary task conditions is deemed an indirect estimate of conscious involvement in motor performance (Lam, Maxwell, & Masters, 2009; Maxwell, Masters, Kerr, & Weedon, 2001) which is guided by verbal-analytical processes and may be disrupted through these conditions. Non-conscious paradigms do not rely on working memory compared to conscious learning systems so dual-task conditions are less likely to disrupt performance of the primary motor task (Zeithamova & Maddox, 2006). Dual task cost reflects the impact of performing simultaneous motor and cognitive tasks relative to performing only a single task. Furthermore, changes or adjustments of technique and execution in movement skills (i.e., fidgets) has been revealed to be another subjective measure of conscious control (Maxwell et al., 2001; Poolton, Masters, & Maxwell., 2005). Maxwell et al. (2001) suggests that more technique changes reflected more hypothesis testing which involves conscious control. Subjective measures of conscious movement control are not always reliable, an example of this is verbal reports where people may be direct in consciously thinking about their movements although they may not have done so initially when performing the task. Overall performance may or may not be influenced by verbal reports but are still frequently used as a measure (Kal, Prosee, Winters, & Van der Kamp, 2018). Verbal reports of the performer's rules, knowledge or methods they used while practicing a motor skill are subjective so may not determine an accurate level of conscious involvement at the time.

1.3.2. Objective measures of conscious movement control

Psychophysiological measures have recently been implemented to better understand and determine the level of conscious processing of motor task performance such as electroencephalography (EEG). EEG is a non-invasive neuroimaging method (Thompson, Steffert, Ros, Leach, & Gruzelier, 2008), where small electrodes are attached to the scalp to measure voltage fluctuations of electrical signals from the brain. EEG is a valuable tool in examining and assessing participants in natural movement tasks and has, for example, faster temporal resolution than functional magnetic resonance imaging (fMRI) (Crosson et al., 2010) which is another method to determine brain activity.

EEG measures brain activity in general and depending on the placement of the electrodes, it can be used to measure the level of verbal-analytical engagement during motor learning performance which may help determine whether conscious engagement (i.e., implicit motor learning) occurs (Zhu et al., 2011). Previous research has used EEG spectral power analyses at individual electrodes on the scalp to give insight into activation at that location or at pairs of electrodes to examine the communication between locations (EEG connectivity or coherence, Cooke, 2013),such as the verbal-analytical engagement in motor performance (i.e., conscious control). Spectral power analysis transforms time-based EEG data into frequency domain signals which are recorded in Hertz (Hz) (Gross, 2014). Both these measures have been mainly focused on the alpha frequency bandwidth (8-12 Hz). This frequency is, for example, most likely to reflect global cortico-cortical communication in relation to the temporal and frontal regions whereas coherence in higher frequency bandwidths is sensitive to more localized activation of the cortex (Nunez & Cutillo, 1995; Zhu et al., 2011).

Studies analysing cortical processes in relation to motor performance have used EEG spectral power analyses at pairs of electrodes to assess communication between locations (i.e., connectivity, Cooke, 2013; Gross, 2014). The most common measure of communication is EEG magnitude squared coherence which measures synchronicity of brain activity between two electrodes (Nunez & Cutillo, 1995) and the other measure is Inter Site Phase Clustering (ISPC, Cohen, 2014), which is referenced as EEG connectivity.

Zhu et al. (2011) studied and validated the measurement of conscious control through the high-alpha frequency co-activation (connectivity) between the left temporal verbal-analytical (T3/T7) and mid-frontal motor planning (Fz) regions during a golf putting task. EEG connectivity was measured continuously through the golf putting task. The participants who practiced the golf putting task with reduced conscious control displayed less T7-Fz co-activation than those who practiced under high conscious control. When placed under pressure situations, those in the high conscious control group displayed more T7-Fz co-activation implying that verbal-analytical processing of putting movements increased with the added pressure. Another study examined electroencephalography (EEG) activity between the frontal midline (Fz), the left temporal (T3/T7) and the right temporal (T4/T8) while participants were completing a sequential finger tapping task (Zhu et al., 2010). Results showed rapid changes in motor performance in the practice stages and then performance declined due to previous knowledge of the task. Results showed increases of theta power at Fz and beta coherence at T4-Fz meaning that progression through the verbal-cognitive stage is paired with narrowed attention of stimuli and finger movements (Zhu et al., 2010).

EEG and motor performance studies have shown that verbal-analytical engagement in movement planning increases right before initiating movement due to the precise time frame to capture EEG measurements (4-7 sec before) (Haufler, Spalding, Santa Maria, & Hatfield, 2000; van Duijn, Hoskens, & Masters, 2019) or just before movement and just after movement by 1 second (Cooke et al., 2015; Gallicchio, Cooke, & Ring, 2016). EEG coherence can be used to measure the conscious control of a participant when controlling a prosthetic limb which is supported by Parr et al. (2019), where they measured the cognitive load of participants completing motor movements.

1.4 Summary and thesis outline

The conscious burden mentioned in a vast number of studies of prosthetic rehabilitation and use (Gardner et al., 2014; Park & Zahabi, 2022; Paskett et al., 2022; Petrini et al., 2019; Williams et al., 2006) calls for innovative and effective methods to alleviate this burden for all. There has been research done that suggests conscious control in amputees increases when using a prosthetic limb (Parr, 2018; Parr et al., 2019; Rackerby, Lukosch, & Munro, 2022; Winkler, 2009) however, an objective measure is yet to be performed to clearly show the levels of conscious control. Measuring cognitive processes related to conscious control while performing a motor task will provide the initial evidence to establish how intuitive control of prosthetics can be obtained. EEG is beneficial to assess the cognitive processes in real time while doing a movement task.

This thesis will examine the verbal-analytical engagement (i.e., T7-Fz connectivity) while participants do a simple and complex reaction time task using a 3D printed robotic arm and their own arm. The purpose of this study is to gain a better understanding into what activity is happening in the brain while a participant is activating a robotic limb in comparison to their own arm. The research will assess neural activity to establish empirically whether use of a robotic arm does increase the conscious processing of movements (i.e., increased verbal-analytical engagement). Firstly, the use of the robotic arm was predicted to show increased reaction times for the computer-based task. Furthermore, we predicted that use of a robotic arm would elevate conscious motor control compared to using own arm during the performance of the computer-based reaction time task. This would be portrait by higher dual-task costs (i.e., difference between dual-task and single task) for the robotic arm condition compared to own arm, for reaction time and verbal-analytical engagement during the reaction time task. Chapter two will describe the methods and results of this study.

Chapter 2: Marks of conscious engagement when performing a motor task with or without a robotic arm

2.1 Abstract

Prosthetic rejection rates are high due to the conscious burden placed on individuals attempting to learn how to use prosthetic limbs effectively and intuitively. Conscious motor control is defined as the level of awareness of an individual performing a movement related skill or task, where the higher the conscious control the more an individual is thinking of their movements while executing them. In this study, electroencephalography was used to measure T7-Fz connectivity of participants (*n* = 16) while they completed a reaction time-based task with simple and complex conditions using a robotic arm when compared to their own arm. A dual task of tone counting was added, and dual-task cost was examined. We hypothesized that use of the robotic arm would increase conscious control when completing the reaction time tasks when compared to own arm. Results showed a higher dual-cost T7-Fz for the complex condition compared to the simple condition for the robotic arm. We concluded that use of a robotic arm increases verbal-analytical engagement when performing a motor task compared to using the own arm.

2.2 Introduction

Prosthetic hand rejection rates are considerably high (44%; Salminger et al., 2022) but varies among recent studies (Kerver, van der Sluis, van Twillert, & Krabbe, 2022; Parr et al., 2022). Difficulty performing everyday activities and overall dissatisfaction with the function comfort of the prosthetic are leading causes of the increased rates of abandonment (Biddiss & Chau, 2007; Resnik, Borgia, Biester, & Clark, 2021; Smail, Neal, Wilkins, & Packham, 2021). Prostheses development and management is important for the rehabilitation of amputees and individuals missing limbs. Learning to control a prosthetic limb is often described as a conscious burden (Parr et al., 2019). The conscious burden is mainly explained by the elevated conscious motor control (i.e., the level of awareness of one's movements) needed to control the prosthetic limb.

An example of conscious control is doing a movement task for the first time when techniques are learned and adapted to make the movement more autonomous which eventually reduces the conscious control (Maxwell, Masters, & Eves, 2003). The addition of a secondary task creates more pressure to perform the primary motor task but is a beneficial measure of consciousness. Dual-task cost is the relative change in performance under dual versus single task conditions. Reaction time tasks with simple and complex conditions (choice of response) can be used alongside the dual-task paradigm to measure different levels of conscious control. In the paradigm, reaction time can be measured with (dual-task) and without (single-task) performance of a secondary task like tone-counting. Measuring conscious control through EEG is providing more information about developing new technologies to help with rehabilitation processes such as prosthesis use. EEG connectivity between T7-Fz is measured to show the level of conscious control at certain points in time when doing a reaction time task in simple and complex conditions with a concurrent secondary task.

Due to the conscious burden many of the users face when fitting, wearing and moving their prosthetic, this study aims to measure conscious control efficiently and effectively while future studies may target the reduction of conscious control. This thesis examines the connectivity of T7-Fz while participants do a simple and complex reaction time task using a 3D printed robotic arm and their own arm. The purpose of this study is to gain a better understanding into what activity is happening in the brain while a participant is activating a robotic limb in comparison to their own arm. The research will assess neural activity to establish empirically whether use of a robotic arm does increase the conscious processing of movements. We predicted that use of a robotic arm would elevate conscious motor control (i.e., T7-Fz connectivity) compared to using own arm for a simple and complex computer-based reaction time task under single and dual secondary task load (tone-counting). It was expected to see high reaction times with the robotic arm when compared to the arm and it was also expected to see higher reaction times with the dual-task when compared to the single-task (i.e., dual-task cost).

2.3 Method

2.3.1 Participants and Design

Forty-six abled-bodied people were recruited to participate in this study, only 16 provided accurate EEG recordings (mean age = 21.56 years, SD = 3.12 years, female = 6). All participants had normal or corrected vision. A repeated measures within subjects design was adopted where each participant completed a reaction time task with their own right arm and again with the robotic arm. The order of starting the experiment with the robotic arm or their own arm was counterbalanced within participants. The study received ethical approval from the University Human Research Ethics Committee.

2.3.2 Task

The participants were asked to perform 12 blocks consisting of six blocks of each ten reaction time trials with their own right arm (own arm condition) and six blocks of ten trials with the robotic arm (robotic arm condition) (see Figure 2.1). The reaction time trials consisted of pressing a key on the keyboard as fast as possible when seeing either a blue or green screen. Before each block of ten trials there was an instruction slide informing them of what they needed to do, once they read through that they could begin the block. Between each trial was a white screen saying to press spacebar when ready and once pressed a black screen appeared for a random delayed amount of time (1sec, 1.5sec, 2sec, 2.5sec or 3sec), then the green or blue stimuli would appear prompting them to make a response as fast as possible. Participant were informed when the block was finished and instructed to read the instructions prior to starting the next block.

The ‘2’ key was assigned to the blue screen and the ‘3’ to the green screen. The participants were instructed to use the pointer finger for the ‘2’ key and the middle finger for the ‘3’ key. To activate the correct finger of the robotic arm, the participants were instructed to wave their wrist inwards to activate the robotic pointer finger and wave their wrist outwards to activate the robotic middle finger. The reaction time task consisted of either a simple choice reaction time task (4 blocks per condition) or a complex reaction time task (2 blocks per condition). The simple choice reaction time task consisted of only seeing one colour screen (i.e., green, or blue) requiring one key being pressed (i.e., either ‘2’ for a blue screen or ‘3’ for a green screen). The complex reaction time task consisted of seeing the blue and green screen, for which participants had to press the correct key. Within the six blocks for either their own arm or robotic arm there where three blocks with an additional secondary tone counting task. The tone counting task consisted of participants hearing low and high tones throughout the blocks, they were asked to count only the high tones in their head and report the number to the researcher after completing the block.

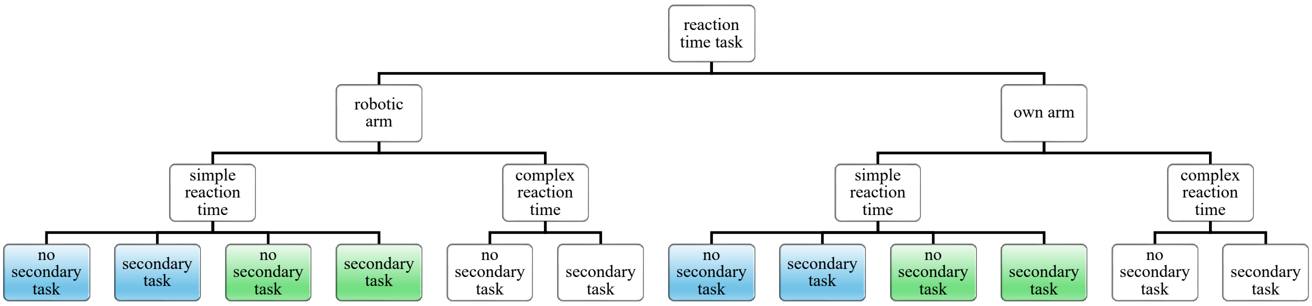

Figure 2.1. Summary of the 12 blocks each participant completed. Six blocks for robotic arm and six blocks for own arm, simple reaction time means one stimulus was presented throughout

the block (blue screen or green screen) and complex reaction time means both stimuli were presented throughout the block (blue screens and green screens).

2.4 Materials

2.4.1 Robotic arm

The 3D printed robotic forearm was designed so the pointer and middle fingers were coded to press a key on a keyboard motion (see Figure 2.2). The robotic arm was placed on the table next to the computer where the participant did the reaction time task, they were not in physical contact with the arm. The robotic arm was connected to a computer and controlled via an electromyography (EMG) sensor band (Myo Armband) which was placed around the top of the forearm near the elbow. The computer ran a coding software, Myo Armband Manager to activate the robotic arm when a threshold of activity was achieved. The calibration of the Myoband took approximately 2 minutes where the program ran through different hand and finger movements (relaxed, make a fist, fingers spread wide, wave inwards and wave outwards). To activate the middle finger of the robotic arm, participants waved their hand from the wrist outwards and to activate the pointer finger of the robotic arm they waved their hand from the wrist inwards. There was an approximate delay of activation of about 0.3 seconds before the robotic fingers pressed the keys.

Figure 2.2. 3D printed robotic arm, only pointer and middle fingers are activated through the Myoband.

2.4.2 Reaction time task software

The reaction time experiment was created on a software program called OpenSesame (version 3.3.14) which is used in building experiments for psychology, neuroscience, and experimental economics.

2.4.3 Tone counting software

Six of the 12 blocks of trials added a secondary task of tone counting where participants heard high (1000 Hz) and low (500 Hz) pitched tones at set intervals and in a randomized order. The tones were played through a computer software (Labview Application Builder 2010, National Instruments Inc., Austin, TX).

2.4.4 Electroencephalography

EEG data was used to assess cortical activity during the reaction time task. EEG was recorded from (5) active electrodes: Fp1, Fz, Cz, FC1, T7. Additionally, two electrodes were placed on the right and left mastoids (Neuroprene 8-electrode cap, Neuroelectrics, Barcelona, Spain). Common Mode Sense (CMS) and Driven Right Leg (DRL) electrodes were used to increase the common mode rejection ratio of the EEG signals. EEG signals were amplified and digitized at 1024 Hz, with 24-bit resolution (Neurosurfer, Neuroelectrics, Barcelona, Spain).

2.5 Procedure

Participants were informed about the context of the study and read through the experiment details. After signing the informed consent, the participants were instructed to fill in the demographical information and questionnaires prior to the beginning of the procedure. The EEG cap and sensors were fitted to the participants head and a 1-minute EEG baseline resting state measurement was performed (30 seconds closed eyes and 30 seconds open eyes). Then the Myoband was placed around their right forearm and calibration was performed for each participant.[1] Thereafter, the participants were set up to start the computer-based reaction time tasks, which they performed with their own arm and the robotic arm.

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[1] The Myoband calibration was performed for all participants at the beginning of the experiment to limit interruption throughout the blocks of trials.

2.6 Analysis

2.6.1 Reaction time task

Reaction time was measured in milliseconds through OpenSesame from the instance the key was pressed. Once the stimuli appeared, the time started until either key was pressed. The score was noted a 1 for correct response and a 0 for incorrect response. Dual-task costs express changes in performance of single-task performance compared to the dual-task performance (i.e., dual task score – single task score).

2.6.2 EEG dual-task cost

EEG signals captured during each block of trials were processed offline with EEGLAB software (Delorme & Makeig, 2004) running on MATLAB (Mathwork, Inc., USA version 2022b) to compute the connectivity measure. The EEG data was analysed by first generating epochs consisting of 2s prior until 1s after the target appeared (i.e., blue or green screen) for each trial. Thereafter, the data was resampled to 250 Hz and band pass filtered (1-35Hz band pass filter), referenced to the average of the two mastoids and de-trended. Baseline correction (200ms before time of interest) was completed, and EMG and electrooculography (EOG) artefacts were removed using Blind Source Separation (AAR plug in; Gomez-Herrero et al., 2006), and least mean squares regression (Gomez-Herrero et al., 2006; Haykin, 1996). A threshold-based artifact removal procedure was performed, deleting epochs with values ±75 µV to clean the signal (Deeny, Hillman, Janelle, & Hatfield, 2003). Exclusion of participants from further analysis occurred if too many epochs (more than 25%) had to be deleted. The alpha frequency band (8–12 Hz) was adjusted for each participant based on their individual alpha frequency (IAF) peak, determined from the baseline measure (IAF toolbox, Corcoran at al., 2018). Phase angles were obtained from the time frequency analysis and were used to compute intersite phase clustering connectivity (ISPC, Cohen, 2014) between the left temporal

(T7) and frontal (Fz) regions in the high-alpha frequency band for the 200ms prior to seeing the screen and 200ms after seeing the screen (i.e., 400ms in total). We calculated the $\mathrm{ISPC}_{\mathrm{time}}$ using the following function:

$$\mathrm{ISPC}_{xy}(f) = \left| n^{-1} \sum_{t=1}^{n} e^{i(\theta_x(tf) - \theta_y(tf))} \right|$$

N is the number of data points; *i* is the imaginary operator; θ_x and θ_y are the phase angles of the recorded signal at two different scalp locations; *t* is the time point and *f* is the frequency bin. The $e^{i(\theta_x(tf)-\theta_y(tf))}$ represents the complex vector with magnitude 1 and angle $\theta_x - \theta_y$; $n^{-1} \sum_{t=1}^{n} (.)$ denotes averaging over time points, and |.| is the module of the averaged vector (Cohen, 2014; Lachaux, Rodriguez, Martinerie, & Varela, 1999). ISPC is given as a value between 0 (no functional connection) and 1 (perfect functional connection). Finally, values were Z-transformed (inverse hyperbolic tangent) to ensure normal distribution (Gallicchio et al., 2016).

2.6.3 Statistical Approach

The EEG dual-task cost, reaction time dual-task cost and score dual-task cost were subjected to a 2 x 2 repeated measures analysis of variance (ANOVA): Condition (Simple or Complex) x Tool (Arm or Robotic arm). The tone counting performance during the dual-task trials was also subjected to a 2 x 2 repeated measure ANOVA: Condition (Simple or Complex) x Tool (Arm or Robotic arm). Sphericity and normality checks were performed when necessary. When main effects or interactions were found, additional ANOVAs and post-hoc tests (Bonferroni corrected) were conducted. Effect sizes are reported as partial η squared (ηp^2). All statistical tests were performed using SPSS (IBM, version 29.0) computer software. Significance was set at $p = .05$ for all statistical tests.

2.7 Results

2.7.1 Reaction Time dual-task cost

The results revealed no main effect of Tool, F(1,15) = 0.67, $p = .427$, $\eta_p^2 = .04$ for the reaction time dual-task cost. There was also no main effect of Condition, F(1,15) = 0.40, $p = .535$, $\eta_p^2 = .03$. However, there was a Tool x Condition interaction effect revealed, F(1,15) = 9.70, $p = .007$, $\eta_p^2 = .39$. With post-hoc analysis revealing the complex condition had a significantly ($p = .034$) higher reaction time dual-task cost for arm compared to robotic arm. No significant effects were revealed for the simple condition. Furthermore, post-hoc analysis revealed participants own arm had significantly ($p = .009$) higher reaction time dual-task cost during the complex condition compared to the simple condition. No significant effects were revealed for the robotic arm (see Figure 2.3).

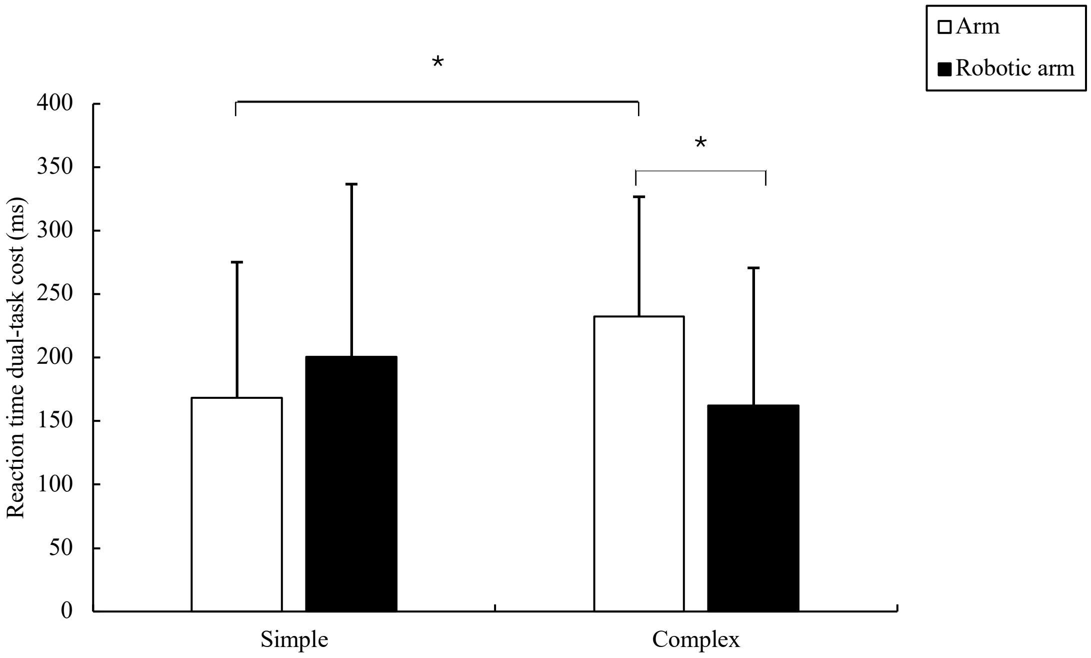

Figure 2.3. Reaction time dual-task cost (ms) of arm and robotic arm in complex reaction time task. Error bars represent standard error of the mean (*$p < .05$).

2.7.2 Score dual-task cost

Neither a main effect of Tool, F(1,15) = 2.35, $p = .146$, $\eta_p^2 = .14$, nor a main effect of Condition, F(1,15) = 3.08, $p = .100$, $\eta_p^2 = .17$, were present for the score dual-task cost. Furthermore, no Tool x Condition interaction effect was revealed, F(1,15) = 1.188, $p = .191$, $\eta_p^2 = .11$ (see Table 2.1).

Table 2.1. Score dual-task cost mean and standard deviation.

	Arm		Robotic Arm	
	M	SD	M	SD
Simple	0	0	0.063	1.77
Complex	-0.75	0.25	0	0.816

2.7.3 EEG T7-Fz Connectivity dual-task cost

Neither a main effect of Tool, F(1,15) = 0.03, $p = .858$, $\eta_p^2 < .01$, nor a main effect of Condition, F(1,15) = 2.74, $p = .119$, $\eta_p^2 = .15$, were present for the T7-Fz connectivity dual-task cost. However, a Condition x Tool interaction, F(1,15) = 5.89, $p = .028$, $\eta_p^2 = .28$ (see Figure 2.4) was revealed. Post-hoc analysis revealing a significantly ($p = .029$) higher T7-Fz connectivity dual-task cost for the complex condition compared to the simple condition for the robotic arm. No significant differences were found for the arm. There was also no significant difference between the robotic arm and the arm for the simple condition, nor for the complex condition.

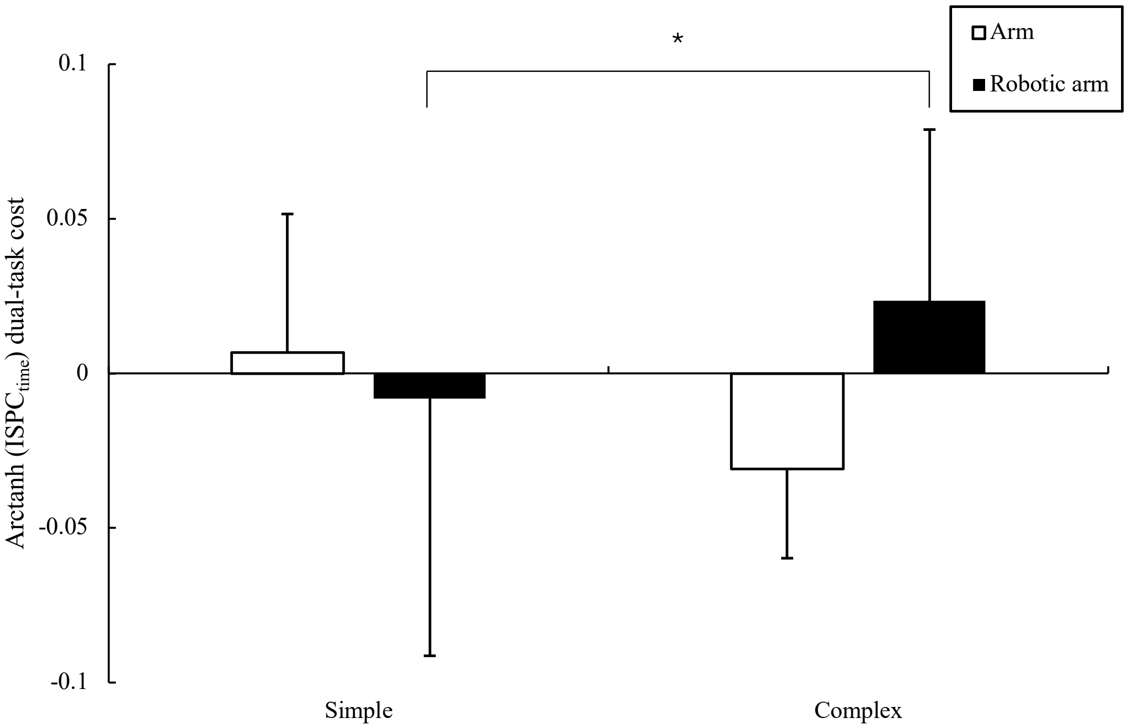

Figure 2.4. T7-Fz ISPC$_{time}$ connectivity dual-task cost during each condition for each tool. Error bars represent standard error of the mean (*$p < .05$).

2.7.4 Tone counting accuracy

Neither a main effect of Tool, F(1,15) = 0.96, $p = .343$, $\eta_p^2 = .06$, nor a main effect of Condition, F(1,15) = 0.51, $p = .825$, $\eta_p^2 < .01$, was revealed. A Condition x Tool interaction, F(1,15) = 0.99, $p = .335$, $\eta_p^2 = .06$ was also not revealed (see Table 2.2). These results indicated that the participants allocated equal attention to the tone counting task in both the simple and complex condition, and when performing the task with the robotic arm or own arm.

Table 2.2. Tone counting percentages score mean and standard deviation.

	Arm		Robotic Arm	
	M	SD	M	SD
Simple	82.38	16.38	83.25	16.87
Complex	79.69	20.99	87.31	13.30

2.8 Discussion

This study was conducted to examine whether using a robotic arm during a reaction time task would increase the amount of conscious control via behavioural and cognitive measures. The reaction time task consisted of participants pressing the correct key as quickly as possible when either seeing a green or blue screen appear. A repeated measures within subject's design was adopted measuring reaction time, score and T7-Fz connectivity dual-task cost while participants performed the choice reaction time task under simple task conditions (i.e., 1 choice reaction time) and complex task conditions (i.e., 2 choice reaction time), using their own arm and again using a robotic arm. The dual-task cost for both conditions was administered by calculating the difference between single-task and dual-task (i.e., additional tone counting task) conditions.

The complex condition had a significantly higher reaction time dual-task cost for the own arm when compared to the robotic arm. However, there were no significant effects of the robotic arm between the complex and simple condition. This might suggest that the own arm condition was more susceptible to the different task conditions compared to the robotic arm condition, revealing higher dual-task interference for the own arm. The simple reaction time task did not reveal significant differences between the own arm and robotic arm. This may mean the act of pressing a key as quickly as possible when prompted by stimuli is easy and does not increase conscious control regardless of arm or robotic arm condition. Overall, there were no main effects of score dual-task costs on either tool (i.e., own arm or robotic arm) or condition (i.e., simple or complex reaction time task) and it was found that most participants were accurate in their responses.

Our study is the first to include the measures of conscious control to investigate whether the subjective feeling of 'conscious burden' is also portrait by increased verbal-analytical engagement in robotic arm compared to own arm movement performance. The findings revealed an increase in verbal-analytical engagement (i.e., increased T7-Fz dual-task cost) in robotic arm movement for the complex choice reaction time compared to the simple choice reaction time task. This might indicate increased conscious control engagement for robotic arm movements when performing a complex choice reaction time task. This finding is in line with other studies suggesting how conscious control adds to the conscious burden of learning prosthetic use (e.g., Parr, 2018; Parr et al, 2019; Rackerby, Lukosch, & Munro, 2022).

Chapter 3: General Discussion

3.1 General discussion

The behavioural and cognitive measures seem to reveal opposite results on conscious control in the complex choice reaction time task. The behavioural data might suggest higher conscious control (i.e., higher reaction time dual-task cost) during the complex choice reaction time task for the own arm condition, whereas the cognitive data suggests higher conscious control (i.e., higher T7-Fz dual-task cost) during the complex choice reaction time task for the robotic arm condition. This might suggest that increased conscious control might not necessarily show in the reaction time of participants. There may not be clear changes in performance between the simple and complex conditions with the robotic arm and own arm conditions which could speak to the reliability of the reaction time being inconsistent in the myoband activating the robotic arm. Participants may have had high conscious control to think about which movement to make to activate the robotic arm correctly and that process of movement was quicker than thinking about which finger to press on their own arm. Despite the differences in behavioural and cognitive results, the findings of this study do reveal that the conscious burden is also shown in brain activity indicating higher verbal-analytical engagement in robotic arm movement compared to own arm movement. This finding is important for further studies developing potential new learning interventions which could lower the verbal-analytical engagement – and thus the conscious burden - in learning to control a prothesis.

3.1.1. Learning interventions to promote intuitive control in prosthetic limb learning

3.1.1.1. Implicit motor learning

One potential manner of reducing the conscious burden in prosthetic learning is implicit motor learning interventions. Implicit motor learning involves the acquisition of a motor skill without a cognitive increase in verbal knowledge about the specific skill (Masters, 1992). Zhu et al.

(2011), used the golf putting task to compare learning implicitly versus explicitly (i.e., high verbal knowledge accumulation) and supported the notion that implicit learning displays lower verbal-analytical coherence (i.e., T7-Fz coherence) while performing a motor task. Researchers have created paradigms such as error-reduced learning, analogy learning and dual-task learning to attempt to reduce conscious control of movement (Masters, van Duijn, & Uiga, 2019).

The learning paradigm of error-reduced learning applies constraints to reduce errors and garner an increase in successful outcomes by increasing task difficulty gradually (Maxwell et al., 2001). Errorless learning is likely to reduce hypothesis testing and accumulation of conscious knowledge (i.e., promote implicit motor learning). Error-reduced learning has proven to be beneficial to motor learning, for example, Maxwell et al. (2001) asked participants to perform a golf putting task where the distances to putt either got gradually further away (i.e., error-reduced learning), nearer (i.e., errorful learning) or distances were performed in a random order. They found the errorless group made fewer errors than the errorful group in the retention test. When performing under pressure situations, Maxwell et al. (2001) concluded that errorless learning is more implicit in skill acquisition. Error-reduced learning has also found to be beneficial for rehabilitation purposes, revealing better outcomes for people with brain injury (Clare & Jones, 2008) and prosthetic fittings where people using the errorless technique made fewer mistakes while putting their prosthetic on (Donaghey, McMillan, & O'Neill, 2010). The benefit of making less mistakes is the knowledge acquired in being successful in a movement is learned and in turn facilitates memory performance (Gillen, 2009).

Movement analogies intend to reduce task relevant rules into a single metaphor that when focused on, elicits an accurate movement or skill (Masters, 2000). By providing a movement analogy, learners have less access to explicit rules about the mechanics of their movements (i.e., promoting implicit motor learning) compared to learners receiving explicit rules on the movement. One study looked at analogy learning through teaching people a top-spin forehand table tennis shot where some were provided with an analogy and others were told explicit verbal rules (Liao & Masters, 2001). When the analogy learners reduced their cognitive anxiety, they performed more successfully under pressure when told they were performing worse than others (Liao & Masters, 2001). Another study applied analogy learning to a basketball movement where participants were told to finish a shot like they are reaching into a cookie jar as opposed to an explicit instruction about their shoulder or arm movements (Lam, Maxwell, & Masters, 2009). Results showed a slight performance increase for those in the analogy group as they learned their skills implicitly (Lam, Maxwell, & Masters, 2009).

Dual-task learning is an implicit motor learning paradigm that adds a secondary cognitive task to be performed alongside a primary motor task (Masters, 1992; Masters, 2000). Dual-task learning has been shown to reduce the propensity for conscious processing of movement promoting more non-conscious motor processing (i.e., implicit motor learning, Masters, 2000). While not all research has shown to support dual-task learning (Gucciardi & Dimmock, 2008; Mullen & Hardy, 2000), there are accounts where dual-task practice enhances learning (Goh, Sullivan, Gordon, Wulf, & Winstein, 2012). Goh and colleagues (2012) examined which factor of a secondary task (difficulty level or engaged processes) is more critical in understanding the dual-task benefit (Goh, Sullivan, Gordon, Wulf, & Winstein, 2012). There was a simple reaction time task and a more difficult choice reaction time task while practicing a lever trajectory arm task and they found those who engaged in similar processes as the primary task had enhanced motor learning and demonstrated high dual-task cost (poor reaction time) during practice (Goh, Sullivan, Gordon, Wulf, & Winstein, 2012). Jackson, Ashford, & Norsworthy (2006), argued that the diversion of attention to a secondary task could affect the disruptive residual conscious processing of movements from single-task performance. Thus, dual-task learning is generally not ideal for novice performance (Beilock, Bertenthal, McCoy, & Carr, 2004) however it can be effective for skilled performers of certain motor skills (Jackson, Ashford, & Norsworthy, 2006; Koedijker et al., 2011).

Studies surrounding dual-task learning have been apparent in a range of prosthetic interventions as well (Losier, Englehart, & Hudgins, 2011; Omana et al., 2023; Raveh, Friedman, & Portnoy, 2018). Raveh, Friedman, & Portnoy (2018), for example, examined visual attention in a motor dual-task paradigm using a myoelectric-controlled hand on their right hand. They were instructed to complete a computer game with their left hand while manipulating objects with the prosthetic and while they did not find significant changes in visual attention or performance between the conditions, they concluded that dual tasks are important to use in research on motor skill learning.

3.1.1.2. Gaze training

Parr et al. (2019), revealed gaze training to be beneficial in alleviating the verbal-analytical engagement during a robotic arm movement task. Gaze training uses observational learning principles for a participant to adopt eye-movement behaviours effectively in prosthetic rehabilitation. Observational learning occurs when observing a movement or skill being performed by someone else or with video and images and eye tracking is measured to assess where the focus is being directed (Asadi, Daneshfar, Maleki, & Aiken, 2023). The results showed that gaze training was effective in prosthetic learning, optimising visual attention and reducing conscious control (Parr et al., 2019).

3.1.1.3. Neurofeedback training

Another potential learning intervention could be neurofeedback, which involves recording and displaying EEG activity in real time while an individual develops strategies to control their brain activity levels (Sidhu & Cooke, 2021). An example of auditory neurofeedback is when the participant is rewarded by a pleasant sound when a specific pattern of brain activation is achieved (Cheng et al., 2015). Sidhu & Cooke (2021) examined the effects of neurofeedback training on participants who performed a motor task (walking) while wearing a leg brace under single and dual-task conditions. The leg brace was used to disrupt and de-automatise the control of walking and the researchers found that walking performance improved after neurofeedback training by decreasing alpha power activity in the central brain region. Neurofeedback training provides increased efficiency of learning motor skills which could then improve development of expertise in movement performance and reduce the conscious burden of prosthetic limb learning (Ring et al., 2015).

3.2 Limitations

There were limitations to this study which may have impacted the results of comparing the robotic arm with own arm in the different conditions. One limitation was the small sample size (16) that was left after the EEG results were analysed of the original 46 participants who completed the reaction time task. Connection and accuracy of the EEG cap and sensors created discrepancies in the raw data therefore only 16 participants results were analysed. Another limitation was that the myoband activating the robotic arm may have had time variance in sending the signal from the participants movement. The robotic arm elicited a delay in pressing the key from when the participant responded to the stimuli. Participants were told to respond as fast as possible but that moving their arm inward or outward quickly wouldn't influence how quick the robotic arm moved. In some instances, the robotic arm would not activate so participants were instructed to make the movement again while thinking about their forearm muscles contracting as the calibration needed enough muscle activation to move the robotic arm. Another limitation is that the participants were able-bodied using a robotic arm instead of people with limb loss using a prosthetic arm. Able-bodied people have full function of their arm and certain movements are autonomous whereas amputees or people with limb loss may have to use more conscious control to make movements which would change the results of this study.

The reaction time task is not a complex motor task as the range of movement was significantly small compared to walking or throwing a ball. Future studies could address range of movement and create other ways to examine motor movement skills to enhance prosthetic limb learning while reducing conscious control. For future research, Parr, Gallicchio, & Wood (2021) conducted an in-depth systematic review of EEG methods for verbal and conscious processing of motor control in sport and human movement which provides recommendations for clear and concise understanding of conscious motor control.

3.3 Conclusion

To conclude, this experiment shows that use of a robotic arm increases verbal-analytical engagement when performing a motor task compared to using the own arm. While the technology surrounding the design and durability of a prosthetic is important, the users' preferences, conscious control and learning effectiveness is just as important to understand. Learning how to use prosthetics effectively and with less conscious control is a major factor in user rehabilitation, satisfaction, frequent use and overall quality of life (Winkler, 2009). Therefore, future research should continue to emphasize human factors such as skill acquisition in the interaction with prosthetic limbs as well as technological factors.

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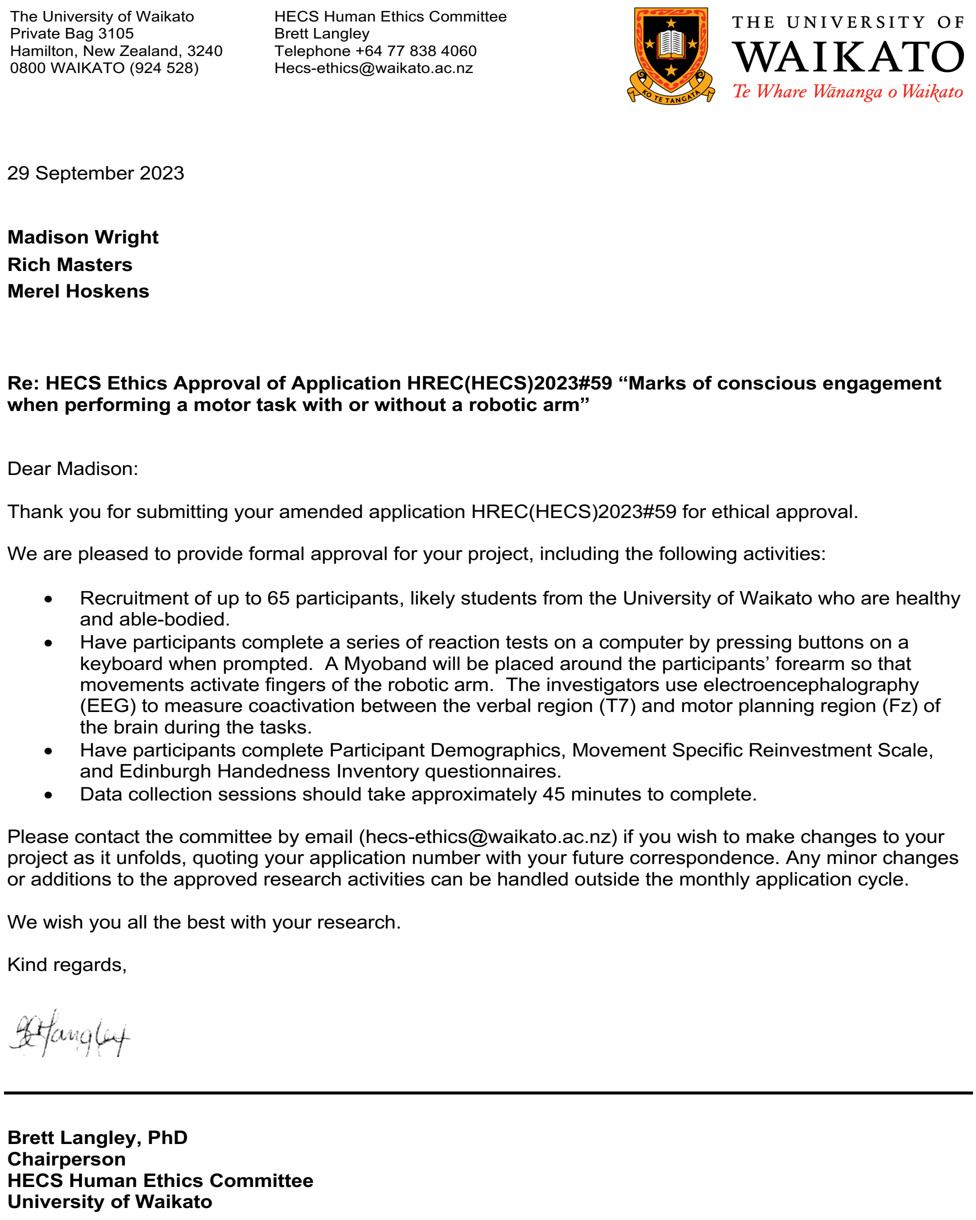
Appendices

Appendix 1 – Ethics Approval



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HECS Human Ethics Committee
Brett Langley
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THE UNIVERSITY OF
WAIKATO
Te Whare Wānanga o Waikato

29 September 2023

Madison Wright
Rich Masters
Merel Hoskens

Re: HECS Ethics Approval of Application HREC(HECS)2023#59 "Marks of conscious engagement when performing a motor task with or without a robotic arm"

Dear Madison:

Thank you for submitting your amended application HREC(HECS)2023#59 for ethical approval.

We are pleased to provide formal approval for your project, including the following activities:

- Recruitment of up to 65 participants, likely students from the University of Waikato who are healthy and able-bodied.
- Have participants complete a series of reaction tests on a computer by pressing buttons on a keyboard when prompted. A Myoband will be placed around the participants' forearm so that movements activate fingers of the robotic arm. The investigators use electroencephalography (EEG) to measure coactivation between the verbal region (T7) and motor planning region (Fz) of the brain during the tasks.
- Have participants complete Participant Demographics, Movement Specific Reinvestment Scale, and Edinburgh Handedness Inventory questionnaires.
- Data collection sessions should take approximately 45 minutes to complete.

Please contact the committee by email (hecs-ethics@waikato.ac.nz) if you wish to make changes to your project as it unfolds, quoting your application number with your future correspondence. Any minor changes or additions to the approved research activities can be handled outside the monthly application cycle.

We wish you all the best with your research.

Kind regards,

Brett Langley, PhD
Chairperson
HECS Human Ethics Committee
University of Waikato

Appendix 2 – Participant Information Sheet

Information Sheet

Project name: Marks of conscious engagement when performing a motor task with or without a robotic arm
Investigators: Madison Wright (Master student), Dr Merel Hoskens, and Prof Rich Masters

Purpose of the study

We are interested in how much conscious control is utilized when doing a simple motor task while using a robotic arm versus own limb. It is important to measure brain activity as doing so will allow us to objectively demonstrate the strength of coactivation between the verbal (T7) region and the motor planning (Fz) region. This is important because it will help us to understand how to promote intuitive use of robotic limbs in the future.

Procedures

You will be asked to visit the motor learning laboratory at Te Huataki Waiora School of Health at the University of Waikato (TT0.10) for about one and a half hours. During this time, you will complete short questionnaires, and learn and practice a novel motor task using your own forearm and while using a 3D printed robotic arm.

Potential risks or discomfort

The risks involved in participating are minimal. For part of the experiment, you will be wearing a neoprene cap with sensors on it. These are completely harmless but may feel a bit uncomfortable to you. The surface electrodes used to monitor your brain activity can cause short-lasting minor skin irritation to participants with sensitive skin. However, this eventuality is unlikely. A very small amount of gel may remain on your head after the experiment. You will also have surface electrodes on parts of your forearm, which will be connected to a 3D printed robotic arm. This may be marginally uncomfortable at times but is harmless.

Confidentiality

Your answers and scores are highly confidential and anonymous. Your name will not be used in connection with the results in any way. The information obtained in this study will be used for research purposes only.

Withdrawal from the study

Your participation is voluntary: you can choose to withdraw yourself from the study at any time. You can withdraw yourself or your data from the analysis up until the point of analysis. There will be no consequences for you if you choose to do so and you do not have to give a reason for doing so.

Other issues, questions or concerns

If you have any questions or concerns about the research, please feel free to contact: Madison Wright (email: madiwright78@gmail.com), Merel Hoskens (email: mhoskens@waikato.ac.nz, telephone 027 8260535) or professor Rich Masters (email: rmasters@waikato.ac.nz, telephone 838 45 00 or ext. 6206).

Appendix 3 – Participant consent form

Te Huataki Waiora - School of Health

The University of Waikato
Private Bag 3105
Hamilton, New Zealand
Phone +64 7 838 4500
www.waikato.ac.nz

THE UNIVERSITY OF
WAIKATO
Te Whare Wānanga o Waikato

Consent form

Project Title: Marks of conscious engagement when performing a motor task with or without a robotic arm.

Researchers: Madison Wright, Dr Merel Hoskens, and Prof. Rich Masters

I _______________ agree to participate as a volunteer in a scientific investigation as an approved part of a research program at the University of Waikato under the supervision of _______________.

The investigation and my part in the investigation have been defined and fully explained to me by _______________ and I understand the explanation. A copy of the procedures of this investigation and a description of any risks and discomforts have been provided to me and discussed in detail with me.

- I have been given an opportunity to ask whatever questions I may have had and all questions have been answered to my satisfaction.
- I understand that the data collected in this research project may be reported in scientific publications, presentations, teaching, and student theses.
- I understand that I am free to withdraw from the project, and ask for my data to be destroyed within three weeks following participation in the research activities, without disadvantage to myself.
- I understand that my data will be anonymized through a coding system, to protect my identity in the research reporting.
- I understand that upon my request I will be given access to a summary of findings from the study when it is concluded
- I am participating in this project of my own volition and I have not been coerced in any way to participate.

Signature of Participant: ____ Date: ____/____/____

I, the undersigned, was present when the study was explained to the subject/s in detail and to the best of my knowledge and belief it was understood.

Signature of Researcher: ____________________________________ Date: ___/____/____

Contact Details for Researchers: If you have any questions or concerns about the research, please feel free to contact: Madison Wright (email: madiwright78@gmail.com, telephone: 0276504849), Merel Hoskens (email: mhoskens@waikato.ac.nz, telephone: 027 8260535) or professor Rich Masters (email: rmasters@waikato.ac.nz, telephone 838 45 00 or ext. 6206).

Appendix 4 – Demographics

Participant Demographics

First Name:	
Family Name:	
Date of Birth:	Age:
Gender (circle) : Male / Female	
Handedness (circle): right hander / left hander	