

**Exploring Factors Associated With Upper-Limb  
Prosthesis Embodiment: A Mixed-Methods Approach**

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## List of publications

Hodrien, A., Galpin, A. J., Roberts, D. J., & Kenney, L. (2017). Exploring the impact of hand movement delays and hand appearance on myoelectric prosthesis embodiment using Immersive Virtual Reality. *Annual Review of Cybertherapy and Telemedicine*, 15.

### Abstracts

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### Poster

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## Presentations

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## Abbreviations

ABIS	Amputee Body Image Scale
AR	Augmented Reality
CPU	Central Processing Unit
DCA	Directed Content Analysis
EMG	Electromyographic
FBI	Full-Body Illusion
FF	Fingers Flickering
GT	Grounded Theory
HIM	Hand Inappropriate Movement
HIP	Hand Incorrect Position
HMD	Head-Mounted Display
HS	Hand Switches
HV	Hand Vanishes
IF	Incorrect Fingers
IPA	Interpretive Phenomenological Analysis
IVR	Immersive Virtual Reality
NCF	Number of Correct Fingers
NHS	National Health Service
PE	Prosthesis Embodiment
PIS	Participant Information Sheet
PLP	Phantom Limb Pain
PLS	Phantom Limb Sensations
RHI	Rubber-Hand Illusion
RLP	Residual-Limb Pain
SCL	Skin Conductance Level
SCR	Skin Conductance Response
TENS	Transcutaneous Electrical Nerve Stimulation
TMR	Targeted Muscle Reinnervation
VHI	Virtual-Hand Illusion
VR	Virtual Reality

## Abstract

Current rejection rates among upper-limb prosthesis users are particularly high. A significant psychological factor associated with prosthesis use is the extent to which users feel their prosthesis is a natural part of them (termed Prosthesis Embodiment [PE]). Many researchers and clinicians suggest that encouraging PE should be an aim of rehabilitation. However, the factors influencing PE, how PE changes over the user's lifetime, and the potential clinical consequences of PE, are currently unclear.

In Study 1, in-depth qualitative email interviews were conducted with 10 upper-limb prosthesis users to explore both factors influencing and resulting from PE, via a qualitative Directed Content Analysis. Participants reported an unexpectedly wide range of both influences (e.g. type of prosthesis) and outcomes (e.g. better prosthesis proficiency). Temporary changes to PE were more noticeable to the user than a gradual change over time. These findings were then used to design a quantitative online questionnaire survey for upper-limb prosthesis users (Study 2) in order to follow-up findings in a larger sample ( $N = 34$ ). In addition to statistically confirming most of the expected relationships, potential motivational and social aspects for PE emerged from the analysis. Further key findings are that PE is on a continuum rather than being dichotomous, and that satisfaction with aspects of the prosthesis (e.g., functionality) is also a major factor. An Immersive Virtual Reality (IVR) study was conducted with 31 anatomically-intact participants to explore experimentally how the prosthesis control method influences PE (Study 3). Body ownership techniques were utilised in a virtual-hand illusion paradigm, combined with motion tracking of a myoelectric prosthesis. This tested the relative impact of electromyographic (EMG) control (via muscle flexes) on virtual PE compared to anatomical-hand control. Results indicated the feeling of agency and skin conductance response to a virtual threat to the prosthesis were similar between the conditions. However, the feeling of ownership was significantly reduced with EMG control of the prosthesis, suggesting the influence of control method on PE, and may be a key factor for rejection.

The results indicate there are a much greater range of influences and outcomes of PE than previously expected or explored, and that IVR prosthetic simulations may provide a method to test specific factors in a controlled setting. Understanding such factors could potentially inform prosthetic design, and ultimately aid in rehabilitation.

## Chapter 1: Introduction

This chapter will introduce the background to the thesis topic, briefly cover the focus of the research, methodological issues faced across the research development, aims and structure of the thesis.

It is estimated that one out of 1,000 people in the UK is an amputee (Bournemouth University, 2013). Whilst this might seem an insignificant number, the potential impact on the person is far from insignificant, with the loss of a limb disturbing bodily integrity, affecting both the psychological and physical condition of the person (Holzer, Sevelde, Fraberger, Bluder, Kicking, & Holzer, 2014). Also, for those born missing part of their limb (congenital limb absence) certain social rituals involving the body may be difficult and social contact may be reduced (Murray, 2005). Limb loss or absence can result in an impact on physical activities, suffering phantom limb pain, disrupted body image, and a reduced quality of life (to be covered in detail in the next chapter).

Prostheses offer people who have lost a limb a chance to potentially restore some functionality interacting with the environment, along with approximating the visual presence of an anatomical limb (Murray, 2004). Upper-limb prostheses can vary with the terminal device being either hand or hook-shaped, and actuation mode either being passive (cosmetic prostheses), body-powered, or electric (myoelectric prosthesis) to address various individual needs (Biddiss & Chau, 2007). Myoelectric prostheses are controlled via electromyographic (EMG) signals arising from muscle within the user's residual limb (i.e., the remaining part of their arm), which are measured by electrodes within the prosthesis (Muzumber, 2004). The signal processed by the electrodes controls the hand to open or close depending upon which muscle is flexed (which has particular relevance for a later chapter). Whichever type is used, amputees are encouraged to use these during rehabilitation (Murray & Fox, 2002); however, despite developments in prostheses some amputees reject their prosthetic limb (McFarland, Winkler, Heinemann, Jones, & Esquenazi, 2010). Thus, understanding any potential underlying factors could be of great significance.

A significant, but still largely under-researched, psychological factor identified in the literature is how the user feels towards their prosthesis in relation to their body, with some experiencing it as part of them (Murray, 2004), known as *prosthesis embodiment*

(McLachlan, 2004), whilst others experience it only as a tool. Despite the suggestion of embodiment being an aim of rehabilitation (Murray, 2004), the precise feelings users have towards their prosthesis, factors influencing such feelings, and potential outcomes as a result of the specific feelings are currently unclear. Exploring these areas in greater depth forms the focus of the thesis, with the overall aim of developing knowledge on the processes involved in whether, or to what extent, prosthesis embodiment can occur for a user, along with some of the potential outcomes of this. Additional knowledge hoped to be gained involves the range of ways prostheses are experienced and described, and how such feelings develop or change over time. It is hoped this knowledge will complement this emerging field, and be built upon further, to inform prosthesis design and/or rehabilitation services.

To explore these overall research aims, a qualitative email interview study was completed with upper-limb prosthesis users. This allowed for exploring a large range of factors associated with prosthesis embodiment, taking guidance from suggestions in literature and building from this with newly emerging factors from the interviews. This revealed a large number of potential factors that may be relevant for prosthesis embodiment and suggestions for individual differences in this. Developing from these findings, a survey study tested the factors in a larger sample statistically, to identify if patterns were confirmed.

As a separate, but connected strand of the research, one of these factors influencing prosthesis embodiment, was explored experimentally through development and testing of an Immersive Virtual Reality (IVR) simulation of a prosthesis, utilising a real myoelectric prosthesis, whose movements were motion tracked (using *Leap Motion*) to display virtually on a head-mounted display (*Oculus Rift*). This explored the impact of control method on embodiment, comparing between natural hand movement and control of the prosthesis with muscle flexes. This study was initially envisioned as a stepping stone to a further IVR study, where the impact of delays to the virtual hand and altering its visual appearance on embodiment would be measured. Delays are particularly salient in myoelectric prosthetic control as the delay between intended and prosthetic hand movement includes a fixed (electromechanical delay in the hand) and variable amount (reliability of electrodes picking up the EMG signal), introducing uncertainty over hand behaviour (Chadwell, Kenney, Thies, Galpin, & Head, 2016), which is potentially important for prosthesis embodiment. Work towards this 2<sup>nd</sup> VR study was completed, but technical issues implementing delays with the

motion tracking software and device halted further development. Continuation of this research is suggested in future research avenues later in the thesis.

A lot of preparation work for the completed IVR study needed to be completed beforehand. In order not to disrupt the flow of the method chapter for this study, the detailed information is not included there, instead referred to and included in the Appendices. Background preparation work included a variety of areas to help design the study and have confidence in its methodological constraints. Firstly, the IVR demo (to be used in experiments) being developed has an inherent degree of latency, i.e., the delay between actual hand movement and presentation of the virtual hand moving. This is produced by the motion tracking device and hardware running the IVR demo. In order to understand whether the optimal latency of the demo would be acceptable for inducing embodiment, an in-depth review of psychological embodiment studies was necessary. Thus, studies aiming to explore or induce embodiment, in particular those most relevant to the IVR study focusing on visuo-motor stimulation studies (where embodiment was induced via active movement), were explored. This review aimed to identify how embodiment is specifically affected by delays introduced in stimulation to inform the feasibility of the study based on the VR technical constraints (later referred to as an asynchronous group) along with further mechanical delays from the prosthetic hand.

Two potential concerns were identified with using the Leap Motion device, one being the latency, the other being the device's accuracy in motion tracking of a prosthetic hand. An investigation into these two factors was completed to help identify the overall latency and accuracy the system will provide during experiments along with deciding the best conditions to improve these factors. This was important so that the conditions are conducive to encourage embodiment through minimising latency and maximising accuracy. For testing latency, understanding the potential constraints of the device were first researched, along with guidance to improve this. Next, numerous videos were filmed of my hand moving along with the virtual hand presented on a desktop PC monitor in a variety of conditions. This allowed for the videos to be analysed frame by frame and calculate the delay (in milliseconds, ms) between actual and virtual hand movement. Further to this, the accuracy of the virtual hand was tested, based on a number of pre-defined categories to identify the overall quality of the virtual hand and the circumstances to optimise this. Ultimately, the optimal latency and



accuracy achieved was considered a concern (and thus worthy of testing) but suitable for the experiments to be conducted.

In summary, the thesis aims to:

- 1) Review previous literature relating to prosthesis use and embodiment.
- 2) Identify potential factors associated with prosthesis embodiment in a qualitative interviews study.
- 3) Test factors that potentially encourage or discourage prosthesis embodiment in a survey study with upper-limb prosthesis users.
- 4) Develop and test the feasibility of an IVR simulation of a real myoelectric prosthesis.
- 5) Experimentally explore the impact of control method on embodiment of a myoelectric prosthesis in an IVR simulation with anatomically-intact participants.
- 6) Consider avenues for further exploring and testing of prosthesis embodiment.

The structure of the remainder of the thesis is as follows:

Chapter 2 – Literature review.

Chapter 3 – Qualitative study.

Chapter 4 – Survey study.

Chapter 5 – VR study.

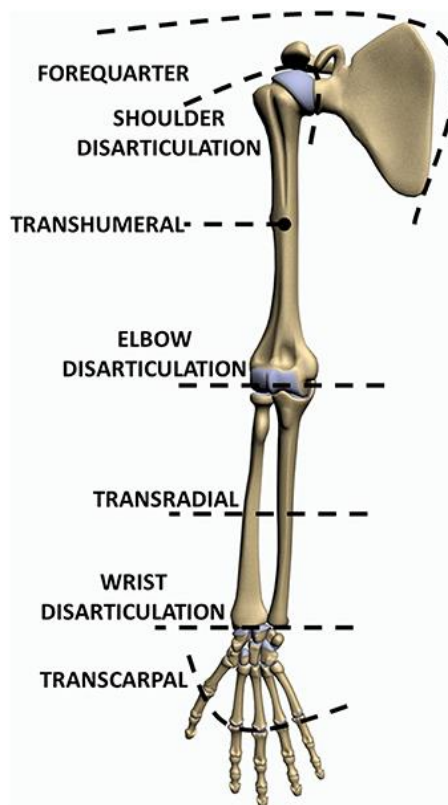
Chapter 6 – General discussion and future considerations.

## Chapter 2: Literature Review

This chapter begins by describing limb absence and its physical and psychological consequences. The types of prosthesis used by people with upper limb absence are then introduced, followed by an overview of the associated problems reported by users, including prosthesis rejection. It will then discuss the area of embodiment, prosthesis embodiment (PE) and factors associated with the occurrence of PE. Following from this, the use of body ownership techniques and Immersive Virtual Reality (IVR) to explore embodiment, along with recent work exploring prosthetics in IVR, will be discussed. These areas will lead to the overall aims of the thesis.

### 2.1 Limb absence

**2.1.1 Types and prevalence.** Limb absence can occur through either amputation or being born missing part, or all of a limb (congenital limb absence). Limb absence can occur to either upper or lower limbs, and can affect one side (unilateral) or both sides (bilateral) of the body. Across 1999-2000, The National Amputee Statistical Database for the UK (2002) recorded there were 5,443 new referrals for amputees to UK prosthetic centres, with only 4.7% being from upper-limb loss; and the same source reported the total number of registered amputees in the UK to be 62,143, with 17.8% of these having upper-limb loss (Datta, Selvarajah, & Davey, 2004). A similar prevalence was noted 5 years later by the database, with 5,239 new referrals between 2004-2005, of which 5% were upper-limb absent individuals (2005). In comparison, Ephraim and colleagues estimated roughly 185,000 amputations occur each year in the US, with a total amputee population of 1.2 million people (Ephraim, Wegener, MacKenzie, Dillingham, & Pezzin, 2005). In 2005, Ziegler-Graham, MacKenzie, Ephraim, Trivison, and Brookmeyer (2008) estimated there to be 1.6 million US citizens with limb loss, including approximately 41,000 with major upper-limb loss (those with a hand amputated or amputation above the hand). There is a greater prevalence of lower-limb (80%) compared to upper-limb (10%) or multiple-limb (10%) loss (Pezzin, Dillingham, MacKenzie, Ephraim, & Rossbach, 2004). Figure 1 shows the different terms used for limb absence at various places along the upper limb.



*Figure 1.* Levels of upper limb absence (taken from Cordella et al., 2016).

Cordella reports the associated incidence rates to be transcarpal (61%), transhumeral (16%), transradial (12%), shoulder disarticulation (3%), wrist disarticulation (2%), forequarter (2%), elbow disarticulation (1%), and bilateral limb loss (3%) (Cordella et al., 2016). However, Jang et al. (2011) found incidence rates of transradial (48%), transhumeral (19%), partial hand and fingers amputation (18%), shoulder disarticulation (7%), wrist disarticulation (7%) and elbow disarticulation (1%), Cordella et al.'s (2016) sample consisted of Italian and UK amputees, whereas those in Jang et al.'s (2011) study were Korean. Also, in the latter study, the sample consisted purely of males. Either of these factors might have influenced the prevalence of specific amputation types. Overall, there appears to be a clear prevalence difference between upper and lower-limb loss. However, the actual prevalence of specific types of amputation is unclear, possibly as a result of surveys only including those referred to limb centres, or researchers simply estimating the prevalence of various types of limb loss.

**2.1.2 Causes.** Reasons for upper-limb amputation can include trauma, peripheral vascular disease and can sometimes be caused by malignancy (Atkins & Robert III, 2012),

with trauma being the most common cause for amputation in young healthy adults (David, Kelly, & Spires, 2013). Congenital limb absence can be due to genetic variation, being exposed to an environmental teratogen (a substance disturbing embryo development), or a gene environment interaction (Ephraim, Dillingham, Sector, Pezzin, & MacKenzie, 2003). Congenital limb absence can be due to genetic variation, being exposed to an environmental teratogen (a substance disturbing embryo development), or a gene-environment interaction (Ephraim, Dillingham, Sector, Pezzin, & MacKenzie, 2003).

**2.1.3 Demographics.** An estimation of prevalence of those with an amputation during 2005, irrespective of cause of amputation, found 42% were at least 65 years old, 65% were men, and 42% were non-white (Ziegler-Graham et al., 2008). Those with upper-limb loss specifically tend to be of a younger age (Hanley et al., 2009) and significantly more males have upper-limb amputations due to trauma (Cordella et al., 2016).

**2.1.4 Need for focus on upper-limb absence.** Hanley et al. (2009) note that most of the amputation literature has focused on lower limb loss, probably due to there being a greater prevalence of lower-limb amputations. McFarland, Hubbard Winkler, Heinemann, Jones, and Esquenaz (2010) suggest that there is less research on upper-limb loss because the population is more heterogeneous than the lower limb amputee population and thus more difficult to study.

There can be a greater impact from upper limb absence compared to lower limb (Baumgartner, 2001). For example, in terms of the degree to which prostheses can replace the missing appearance and function, there remain major challenges to reproducing the delicateness and complexity of movement, along with tactile (sensation via touch) and proprioceptive (perception of limb position) senses of the hand; meaning upper-limb amputees face additional frustration and issues during rehabilitation (Jang et al., 2011). In addition to this, there can be a greater impact due to the hand's functional importance (e.g., involvement in activities of daily living) and social relevance (e.g., expressing ideas, communicating, and showing affection) (Saradjian, Thompson, & Datta, 2008). This justifies the greater need for exploring how and why upper-limb prosthesis users interact, or as outlined later in the chapter, choose not to interact with their prosthesis. Due to the outlined reasons, upper-limb loss will be the focus of this research. Where possible, research specific to upper-limb loss or prosthesis use will be focused on.

## **2.2 Physical impact of amputation**

**2.2.1 Impact on activities.** Upper-limb amputations can have a significant impact on independence and activities, in terms of daily living tasks, work, and socialising (Cordella et al., 2016). A prosthetic limb is intended to restore function as much as possible and limit the disruption caused by limb-loss. Nevertheless, unilateral amputees commonly cease use of their prosthesis, instead using their intact hand to achieve activities of daily living (McFarland, et al., 2010). Further, Jang et al. (2011) found that for unilateral amputees, 39.7% had to stop working following limb loss, 29.3% worked at a different workplace, 10.7% remained at the same workplace but performed different tasks, with only 8.8% remaining at the same workplace and completing the same tasks. For bilateral amputees, 85.3% could not return to work, and the remaining 14.7% worked in a different occupation (Jang et al. (2011).

**2.2.2 Phantom limb sensations.** The peripheral nervous system and central nervous system are altered (in terms of both afferent and efferent signals) by amputations, with consequent phenomena including the emergence of phantom limb sensations (PLS) (Collins et al., 2018). PLS are the feeling that the previously amputated limb is still present, either in an intact form or resembling the previous limb (Murray & Fox, 2002). The phantom hand can be experienced in a similar place to the prosthesis/previous hand, or in an incorrect position, e.g., inside the stump, termed as telescoping (Giummarra et al., 2010). The prevalence of PLS in amputees is high, with studies reporting prevalence rates of 86% and 92% (Mayer, Kudar, Bretz, & Tihanyi, 2008; van Lunteren, van Lunteren-Gerritsen, Stassen, & Zuithoff, 1983). PLS have also been reported to occur in children with congenital limb loss (Mayer et al., 2008).

**2.2.3 Phantom limb pain and other pain.** Most amputees who experience a phantom limb also experience associated pain, which can vary in terms of severity, frequency, and duration (Collins et al., 2018). Phantom limb pain (PLP) incidence rates range from 60-80% and is characterised as burning, throbbing, squeezing, shooting, or stabbing sensations (Nikolajsen & Jense, 2001). Aside from PLP, pain can occur in the stump, known as stump pain or residual-limb pain (RLP; Ephraim et al., 2005) which ranges from a prevalence of 49% (Kooijman, Dijkstra, Geertzen, Elzinga, & van der Schans, 2000) to 71% (Hanley et al., 2009) of those with upper-limb loss. Pain has also been reported in other areas of the body,

including in the non-amputated arm, back, and neck, the prevalence of which ranges from 33% to 64% (Datta et al., 2004; Ephraim et al., 2005).

**2.2.4 Impact of pain.** Many of those with limb loss suffer from chronic pain, often of more than one type, potentially disturbing health and functioning (Hanley et al., 2009). Amputation-related pain has been associated with higher affective distress (Desmond & MacLachlan, 2006), and PLP specifically with both lower subjective well-being (Bosmans et al., 2007) and quality of life (van der Schans, Geertzen, Schoppen, & Dijkstra, 2002). Chronic pain can be disabling (Marshall, Helmes, & Deathe, 1992) and can interfere with both employment (Millstein, Bain, & Hunter, 1985) and participating in social activities (Parkes, 1973).

## **2.3 Psychological impact of amputation**

**2.3.1 Disrupted Body Image.** Aside from the physical issues caused by amputation, there is also the psychological impact of a significant bodily alteration. An amputee must become accustomed to their body with an altered appearance, including both with and without a prosthesis (Atherston & Robertson, 2006). Thus, one of the dominant challenges in adjusting to limb loss involves changes to the patient's identity in terms of a transformed *body image* (Senra et al., 2012). Body image is defined as the thoughts, feelings, beliefs, and attitudes a person holds about their body (Murray, 2004). Such feelings towards a person's body are frequently changing and they consist of psychological, physical, and social components (Flannery & Fariah, 1999).

Breakey (1997) argues that, during rehabilitative interventions, emphasis is largely placed on the physical abilities or limitations of amputees, with little focus on their psychological wellbeing. Specifically, disrupted body image as a result of amputation is an important and overlooked factor in rehabilitation, along with how much body image can influence a person's functional outcome (Wetterhahn, Hanson, & Levy, 2002). However, there have been a number of research studies exploring body image in amputees (e.g., Breakey, 1997; Flannery & Fariah, 1999; Gallagher, Horgan, Franchignoni, Giordano, & MacLachlan, 2007; Holzer et al., 2014; Mayer, Kudar, Bretz, & Tihany, 2008; Murray & Fox, 2002; Novotny, 1986; Rybarczyk, Nyenhuis, Nicholas, Cash, & Kaiser, 1995; Senra et al., 2012; Wetterhahn et al., 2002).

Such studies mentioned above reveal how amputation can impact body image in numerous ways, thus making body image particularly salient for amputees. Whilst body image perceptions are naturally transitory, amputations can have a significant and more permanent impact on body image (as measured by the Amputee Body Image Scale, ABIS, Gallagher et al., 2007). This is evidenced by amputees having a more negative body image perception compared to non-amputees (Holzer et al., 2014). Body image can be affected by an amputee's life experiences, personality, developmental stage, how significant the lost limb was to the person (Novotny, 1986), gender and age (Flannery & Fariah, 1999). Novotny (1986) argues that a disturbed body image is present when a person is unable to accept their new image, and clings onto an earlier self-image. Senra et al. (2012) discovered that amputations can cause not just body image alterations, but also changes to self-identity, influencing an amputee's awareness of the situation, their self-biography and future projections of their self.

**2.3.2 Reduced quality of life.** Amputation can lead to a variety of psychological problems on top of an altered body image. For example, amputees experience a lower quality of life compared to non-amputees (Holzer et al., 2014). Additionally, depression and anxiety have been found to be being highly prevalent in amputees (McKechnie & John, 2014). The psychosocial wellbeing of amputees has also been found to be associated with their body image (Gallagher et al., 2007). A negative body image is related to higher anxiety and depression, along with lower self-esteem and satisfaction with life (Breakey, 1997). This supported similar findings of Rybarczyk et al. (1995) who found that body image disturbance predicted depression, quality of life, and ratings of an amputee's psychological adjustment from a prosthetist. Rybarczyk, Edwards, and Behel (2004) also reported two contrasting cases, the first in which an amputee's negative body image perceptions appeared to contribute to their maladaptive adjustment to limb loss, and a second case where the amputee's positive body image was related to adaptive adjustment to limb loss.

It appears that amputation can lead to a lower quality of life both directly, as a result of reduced ability with daily living tasks, employability, and pain, and also via experiencing disturbed bodily integrity (Holzer et al., 2014). However, it should be noted that other pre-existing health reasons may contribute towards quality of life and/or body image alongside amputation, such as diabetes or obesity. It is also plausible that, if amputation is a cause,

other mediating factors may additionally contribute towards quality of life. Three potential factors are length of time since amputation (Rybarczyk et al., 1995), length of time with a prosthesis and amount of prosthesis use (Gallagher & MacLachlan, 2004). These factors have been found to be associated with general quality of life and quality of social relationships, respectively. Furthermore, Gallagher and MacLachlan found greater satisfaction with the appearance of the prosthesis predicted greater psychological quality of life. This suggests a positive experience with the prosthesis could lead to a more positive life experience overall.

**2.3.3 Perception from others.** Amputees or those with congenital limb loss can be stigmatised and have issues in interacting with anatomically-intact people, leading to their self-identity (how the person views themselves) being harmed (Murray, 2008). Thus, amputees need to adapt to their new body in order to develop a resistance to negative reactions from others and restore self-esteem (Atherton & Robertson, 2006). Novotny (1986) notes that this is due to values in society which focus on vitality and physical fitness, consequently characterising amputation as a sign of failure. Atherton and Robertson (2006) highlight that individuals develop a schema (group of assumptions), focusing on aspects of self-representation, such as personality, gender identity, body shape and weight, and general appearance. As amputation and prosthesis use alters physical appearance, individuals who are more focused on their appearance (appearance schematic) in terms of self-evaluation, are at greater risk of disturbance from their appearance not conforming to the society-endorsed model (Atherton & Robertson, 2006).

## **2.4 Prostheses**

**2.4.1 Purpose of prosthesis use.** Prostheses offer those with limb absence some restoration of functionality, along with an approximation to the visual appearance of an anatomical limb (Murray, 2004). Amputees will be encouraged to use a prosthesis during rehabilitation (Murray & Fox, 2002), and someone with congenital limb absence may choose, or be encouraged by medical professionals, to use a prosthesis. Prosthesis users report that the functionality provided by a prosthesis are useful for engaging in hobbies, mobility, working, and activities of daily living (Van Lunteren et al., 1983).

Beyond restoring or improving function, a prosthesis provides, to a greater or lesser extent, a visual representation of the missing limb. Thus, a prosthesis facilitates the user's



body to reflect one which is considered socially ‘acceptable’ (Novotny, 1986). Consequently, a prosthesis could help an amputee to feel more socially comfortable when in public, with the prosthetic limb’s role of social normalisation important for both amputees and those with congenital limb absence (Murray, 2008). This might account for the findings from one survey in Slovenia that 70% of 414 upper-limb amputees wore their prosthesis only for cosmetic purposes (Burger & Marinček, 1994). Additionally, prosthesis wearing has significant importance for body image restoration (e.g., Saradjian et al., 2008). Thus, wearing a prosthesis can provide the person with a more positive body image, potentially especially important for amputees feeling their pre-amputation body shape restored.

**2.4.2 Types.** There are three prosthesis types which can be provided to upper-limb amputees or those with congenital limb absence, with the terminal device being either hand or hook-shaped, and actuation mode either being passive, or active/functional (Biddiss & Chau, 2007a).

**2.4.2.1 Cosmetic.** Cosmetic prostheses are passive prostheses (i.e., without parts that can be moved with either body or external power) which aim to replace the appearance of the missing body part (Cordella et al., 2016). Users of cosmetic prostheses have noted that they are vulnerable to getting dirty, discoloured, or damaged, with the consequent impact on the fidelity of their appearance (Van Lunteren, et al., 1983). They are a commonly used type of prosthesis, with a prevalence of 80% in one survey (Jang et al., 2011), and have been found to be the preferred prosthesis of choice for recreational activities (Burger & Marinček, 1994).

**2.4.2.2 Body-powered.** Body-powered prostheses are active prehension prosthetic limbs which are controlled via cables and harness around the user’s shoulders (Cordella et al., 2016) offering more functionality than cosmetic prostheses (Ovadai & Askari, 2015). However, these devices are physically demanding to use (Cordella et al., 2016).

**2.4.2.3 Myoelectric.** Another type of active prosthesis is a myoelectric prosthesis. Myoelectric prostheses, are controlled via electromyographic (EMG) signals arising from muscle within the user’s residual limb (the remaining part of their arm), measured by electrodes within the prosthesis (Muzumber, 2004). The signal processed by the electrodes controls the hand to open or close depending upon which muscle is flexed. The transduction of the myoelectric signals, from socket-located electrodes, is influenced by how well the

socket fits the residual limb (Head, 2014). The poorer the fit, the less reliable the transduction. This means that the prosthesis response to a user's intended action (i.e., open or close the hand) can be somewhat unpredictable. This is explained in more detail in the following paragraph.

There is a fixed delay between EMG onset and hand movement (via electromechanical delay in the hand) and this is compounded by less than perfect reliability in the electrodes picking up the EMG signal. Both introduce uncertainty over how the hand will behave (Chadwell, Kenney, Thies, Galpin, & Head, 2016). Saunders and Vijayakumar (2011) note that such prostheses, controlled by EMG electrodes, have an inherent degree of uncertainty. In an experimental study, they found that a prosthesis responding in a fast and predictable manner was associated with a good level of control (better task performance), even in the absence of feedback. However, a prosthesis with random delays (causing uncertainty in how the prosthesis would respond), was associated with a reduced level of control. This highlights the importance of predictable response of the prosthesis based on intended movement for functionality.

**2.4.3 Prosthesis satisfaction.** For this thesis, satisfaction refers to the level of personal contentment the user has with their prosthesis. A study by Davidson (2002) found only 24% of users reported overall satisfaction with their prosthesis, and only 28% were satisfied with its abilities. In another study, users rated their satisfaction with upper-limb prostheses poorly compared to lower-limb prostheses (Saradjian et al. 2008), likely due to the still rather poor degree of functional and cosmetic restoration achievable in upper limb prostheses (Baumgartner, 2001). Millstein, Heger, and Hunter (1986) propose that for prosthetic acceptance (and use) to occur, the prosthesis needs to provide enough comfort, function, and pleasurable appearance. Additionally, satisfaction with these three aspects has been positively associated with quality of life (Matsen, Malchow, & Matsen, 2000).

Saradjian et al.'s (2008) study found that prosthesis satisfaction varied for an individual based on what the limb was compared to; when compared with the lost limb there was less satisfaction with the prosthesis. A user may view their prosthesis as useful for some activities, but not others (Murray, 2009). Hence satisfaction is multifaceted and could vary with context. However, as Biddiss and Chau (2007b) note, the latest in-depth study on prosthesis satisfaction was conducted over 20 years ago (Atkins, Heard, & Donovan, 1996),

and thus changes to prosthesis users' satisfaction as a result of subsequent prosthesis developments may have not been detailed in previous studies. Also, there has tended to be a narrow consideration of a person's relationship with their prosthesis, emphasising prevalence of rates of acceptance and rejection rather than qualitative experience (Murray, 2009).

**2.4.3.1 Functional and comfort satisfaction.** Users report the functional aspects of their prostheses can help with engaging in hobbies, mobility, working, and activities of daily living (Van Lunteren et al., 1983). Despite this, most upper-limb amputees tend to only use their prosthesis for cosmetic purposes (Jang et al., 2011). Myoelectric prosthesis users report experiencing technical unreliability of their prosthesis, in addition to discomfort caused by perspiration within the socket (Van Lunteren, et al., 1983). The difficulty in controlling myoelectric prostheses has been widely reported (e.g., Biddiss & Chau, 2007a) and can lead to rejection of the prosthesis (Biddiss & Chau, 2007b). A user in Saradjian et al.'s (2008) study noted that whilst they could open and close the fingers (as one) and thumb of their myoelectric prosthesis, this capability is far from the full dexterity of an anatomical hand. Body-powered prosthesis users have highlighted the discomfort and range of movement limitations from the harness (Van Lunteren, et al., 1983), and high degree of effort required to operate the end effector (Cordella et al., 2016). Also, four participants in Van Lunteren et al.'s (1983) study reported their prosthesis removed their sense of touch, and felt held back by this as they had good motor function with their forearm stumps. If an upper-limb prosthesis is used, there may be problems engaging in daily living activities, such as getting dressed or eating (Davidson, 2002), along with the burden of the physical effort required for prosthesis use (Van Lunteren, et al., 1983).

**2.4.3.2 Aesthetic satisfaction.** Another aspect of prosthesis satisfaction is the appearance of a prosthesis, identified as important by most users. Aesthetic satisfaction has also been raised as important for prosthesis users in qualitative studies (e.g., Gallagher & MacLachlan, 2001; Legro et al., 1999; Saradjian et al., 2008; Wijk & Carlsson, 2015). A user in Saradjian et al.'s (2008) study highlighted that their prosthesis differed greatly in appearance from their anatomical hand. By contrast, another qualitative study reported one participant's lack of interest in the prosthesis looking like a hand, due to their view of the prosthesis only serving as a tool (Murray, 2004). Despite this, prosthetic appearance is likely to be important for many prosthesis users.

**2.4.3.3 Relationship with body image.** Body image disturbance has been found to have a negative association with factors associated with prosthesis satisfaction (Breakey, 1997; Gallagher et al., 2007; Murray & Fox, 2002), specifically with the aesthetics, function, and weight of the prosthesis (Gallagher et al., 2007). It is plausible that the causal links between prosthesis satisfaction and body image work in both ways. Gallagher et al. (2007) suggest that prosthesis satisfaction influencing body image should be expected, due to the significant cosmetic, social, and functional role the prosthesis attempts to fulfil. Supporting this relationship, Wetterhahn et al. (2002) note that previous research had shown satisfaction with using a prosthesis, and mastering control of it through physical activity, can restore body image, but did not include a reference to support this. However, as a potential example, in Racy's (2004) study, participants directly confirmed the relationship between prosthesis acceptance and acceptance of their altered body image. In one case, a participant recounted how her satisfaction with her prosthesis, which was more functional than the amputated limb, resulted in a more positive perception of her body.

**2.4.3.4 Relationship with prosthesis use.** Another relationship that has been found with prosthesis satisfaction is prosthesis use (Bilodeau, Hébert, & Desrosiers, 2000; Davidson, 2002). However, similar to the body image relationship, the direction(s) of this relationship is unclear; higher satisfaction may increase the chance the prosthesis will be used more; alternatively, greater prosthesis use may increase satisfaction due to a user becoming more skilled with/confident with their device. It has been proposed that use of a prosthesis depends on a user experiencing a sufficient level of satisfaction (Davidson, 2002; Millstein et al., 1986). Also, Murray (2009) notes that use of a prosthesis is one of the best indicators of prosthesis satisfaction (i.e., satisfaction leading to use). However, as Senra et al. (2012) mention, through rehabilitation patients may develop a more positive relationship with their prosthesis (i.e., use leading to satisfaction). Similarly, Delehanty and Traschell (1995) suggest that refusing to use, or being unable to use, a prosthesis causes a reduction in prosthesis satisfaction. These suggestions highlight the potential importance of prosthesis use for prosthesis satisfaction.

**2.4.4 Prosthesis use.** Acceptance of a prosthesis is poorly defined and often just characterised as the opposite of rejection or abandonment of the prosthesis. This means it is unclear how much a prosthesis should be used to be considered 'accepted' by the user. At best, the definition seemingly represents some level of use or not completely abandoning the

prosthesis. Also, rejection itself may be somewhat unclear, not necessarily consisting of a complete non-use of the prosthesis. For example, in one study rejection represented use of the prosthesis once or less per year (Biddiss & Chau, 2007a). Whether a prosthesis will be accepted and used depends on a range of factors, including various physical and psychological benefits and difficulties, outlined below. These may vary between people, depending on each person's circumstances, and the individual perception of the benefits and difficulties will influence whether a prosthesis is used.

It is suggested that a significant proportion of unilateral upper-limb amputees avoid use of their prosthesis, instead using their intact limb for achieving daily activities (Jang et al., 2011). This has been evidenced by real-world testing of myoelectric prosthesis use, which found an over-reliance on the intact limb, compared to a similar reliance on both limbs in anatomically-intact people (Chadwell et al., 2018). Whether a prosthesis is used depends on the motivation of the user (Milstein et al., 1986), with enough motivation needed to cope with the mental effort required to use the prosthesis (Van Lunteren, et al., 1983). Additionally, only some individuals may perceive their prosthesis as embodying ability, due to it enabling performance of physical actions and social roles. However, others could perceive their prosthesis as embodying disability, due to it prohibiting such actions and roles compared to having an intact limb (Desmond & MacLachlan, 2002). The latter perception could occur, as a prosthesis, by definition, represents a diminished body image which is not complete (Jain, 1999).

As mentioned previously, prosthesis satisfaction, but not specifically satisfaction with prosthetic limb abilities, has been associated with prosthesis use (Davidson, 2002). Van Lunteren et al. (1983) emphasise the importance given to the cosmetic appearance by prosthesis wearers. This refers to the natural appearance and unobtrusiveness of the prosthesis, with many prosthesis users paying attention to the appearance (e.g., shape, colour) of the prosthesis. Van Lunteren et al.'s study also found myoelectric, compared to body-powered, prostheses were associated with a greater frequency of use of the gripping function, suggesting use patterns depend on the nature of the prosthesis. Whilst perceptions of the prosthesis (e.g., cosmesis, comfort, function etc.) are subjective they represent attributes of the prosthesis itself. However, there may be additional factors, external to the prosthesis influencing whether it is used.

Other factors which contribute towards use have been found to be amputation level, stump quality, manual dexterity of the prosthesis, and how motivated the person is in using the prosthesis (Millstein et al., 1986). Van Lunteren et al. (1983) found that lower-arm amputations and the level of help provided by other peoples were associated with how much the overall functions of the prosthesis were taken advantage of. They also found that, for myoelectric and body-powered prosthesis users, less than six months between amputation and prosthesis provision, and limited help from others, were associated with use of gripping function.

Some tentative evidence also suggests a potential relationship between phantom limbs and prosthesis use. As previously mentioned, phantom limbs can either be experienced as aligned with the position of the prosthesis or anatomical limb, or not aligned. Whilst not having a large enough sample size to identify a significant association, one study found that, out of nine people with an anatomically-abnormal phantom limb, seven were characterised as having low prosthesis use (Van Lunteren et al., 1983).

**2.4.5 Prosthesis rejection.** Despite technological developments, some amputees reject their prosthesis (McFarland et al., 2010). A review found 20% of upper-limb amputees had stopped using their prosthesis (Biddiss & Chau, 2007a). Reasons cited include difficulty controlling the prosthesis, its functionality, and a lack of comfort (Østlie, Lesjø, Franklin, Garfelt, Skjeldal, & Magnus, 2012). Murray (2004) has mentioned potential factors which influence acceptance of a prosthesis. These include the cosmetic value (i.e., the naturalness of appearance) and how useful the prosthesis is for activities. Also, the prosthesis needing limited maintenance (i.e., looking after or repairing). Additionally, the degree to which the user is realistic in their expectations of the prosthesis may also affect prosthesis acceptance. Whilst physical problems (e.g., physical effort and discomfort) can lead to rejection, these can be partially negated through amputees persevering with their prosthesis, leading to a more natural, automatic use (Murray, 2004). This is possibly highlighted by the positive relationship between prosthesis use and satisfaction (Bilodeau et al., 2000), such that continued use leads to attenuation of physical problems in prosthesis use, and greater overall prosthesis satisfaction.

The acceptance and use of a prosthetic limb are a complicated process, with successful rehabilitation requiring an understanding the psychology of prosthesis use

(Saradjian et al., 2008). However, this has tended to be considered in narrow terms of acceptance or rejection rates (Murray, 2004). To develop a deeper understanding of limb loss and prosthesis use, some researchers have argued for focusing on psychological factors (Breakey, 1997) and/or adopting a qualitative approach (e.g., Desmond & MacLachlan, 2002; Murray, 2004; Rybarczyk et al., 2004; Rybarczyk, Nicholas, & Nyenhuis, 1997; Saradjian et al., 2008; Senra et al., 2012; Sjö Dahl, Gard, & Jarnlo, 2004). Notably, Murray (2004) has highlighted the importance of *embodiment* which will be explained in the following section.

## 2.5 Embodiment

**2.5.1 Embodiment definitions.** A broad definition of embodiment is the sense of having a body (Longo, Schüür, Kammers, Tsakiris, & Haggard, 2008). The literature on embodiment is characterised by disagreement between authors and inconsistent terminology (Longo & Haggard, 2012). Thus, embodiment has been described somewhat differently, Embodiment includes the sub-components *body ownership* and *agency*, the feeling of ownership over one's body and the feeling of being the agent of your actions, respectively (de Vignemont, 2011). Whilst ownership and agency are related to each other (de Vignemont, 2007), a dissociation between them has also been found (Kalckert & Ehrsson, 2012), meaning their exact relationship is unclear.

Embodiment can be defined both explicitly (e.g., feelings of ownership, control, bodily integrity, affective feelings) and implicitly (e.g., an object is embodied if at least some of its properties are processed in the same way as a biological body part (Gouzien et al., 2017). As will be discussed below, some, or all of these implicit and explicit factors can be influenced by interaction with tools and artificial body parts (prostheses and rubber hands, for example) (Giummarra, Gibson, Georgiou-Karistianis, & Bradshaw, 2008). This will be detailed across the following sections.

The neural mechanisms of embodiment involve a model operating via both bottom-up and top-down processes through multisensory integration. Afferent sensory information relating to the body, including visual, proprioceptive, somaesthetic, vestibular, and auditory information, is integrated with efferent information, that relate to motor output and how the body is moving in space (Giummarra et al., 2008). Such processes are suggested to involve multiple areas of the brain, including the extrastriate body area (EBA) and the cortex at the

temporoparietal junction (TPJ) (Arzy, Thut., Mohr, Michel, & Blanke, 2006). The EBA activates in response to images of the human body or body parts along with imagined or actual movements, thus is involved in multisensory integration of body-relevant information. The TPJ also processes such information, along with self-relevant processing, including the sense of agency, distinctions between the self and others, and imagery of the body (Arzy et al., 2006). Arzy et al., highlight that neuroimaging data supports the involvement of the TPJ for coding embodiment, and their own data reveals that brain activity distributed, and with appropriate timing, at both locations is vital for processing the self as embodied and spatially congruent with the body.

**2.5.2 Body schema.** *Body schema* can be defined as the representation of how the body is positioned and configured in space, with the purpose of integrating proprioceptive information from limbs with tactile information from the body (Mayer et al., 2008). A distinction has been made between body schema, the unconscious updating of limb position while navigating the environment, and body image, the conscious perceptions about the bodily form (Longo, Schüür, Kammers, Tsakiris, & Haggard, 2009). Body schema usually updates itself in response to gradual changes to the body, such as in ageing, but can also change with the body having objects incorporated into it, such as a prosthetic limb (Mayer et al., 2008). As mentioned earlier, embodiment can be defined explicitly and implicitly, and body image and body schema relate to embodiment as explicit and implicit factors, respectively. Whilst body image reflects an aspect of embodiment involving conscious thoughts about the nature of one's own body, the body schema reflects unconscious processing of where the body is located (i.e., differentiating between the body and external environment).

Mayer et al. (2008) found that body schema in amputees was influenced by the amount of time the user reported wearing their prosthesis and amount of time since the limb was amputated. Their study concluded that a body schema where the phantom limb is equivalent to the intact limb can be achieved by wearing a prosthesis. However, despite sensing the phantom at the same time as seeing the prosthesis, this does not lead to feeling ownership due to awareness of their lost limb (i.e., having conscious awareness of their limb being absent still). This suggests a potential complication in embodiment with further exploration into factors influencing embodiment needed.



**2.5.3 Tool embodiment.** Through repeated tool use, a person's body schema can be altered to assimilate the object, effectively treating it as extending from the person's arm and hand (Giummarra et al., 2008; Lewis, 2006). Similar regions of the cortex which process complex hand movements also represent the use of tools (Giummarra et al., 2008). This happens because the body schema's role is spatially organising position of limbs, tracking their movement in space and bodily-surface shape. Thus, the brain represents the tool as part of the person's body schema (Lewis, 2006). When the tip of the tool is moved it is perceived as if the hand itself was moving (Maravita, Spence, & Driver 2003; Maravita, Spence, Kennett, & Driver, 2002).

**2.5.4 Prosthesis embodiment.** Research on body image has tended to focus on the influence of amputation and use of a prosthetic limb in terms of affective responses (Murray, 2004). However, as Murray highlights, in the field of phenomenology there exists an alternative form of body image, that of the perceptual bodily experience which is embodied. Embodiment, in this sense, involves a perceptual experience which is immediate and pre-reflective (i.e., prior to self-reflection or evaluation of the perception), with a common example given being the experience of a blind person using a cane where there is a transferral of a sense of touch from the hand to the end of the cane (Murray, 2004). As MacLachlan (2004) notes, "it may be useful to recognise a division between purely perceptual aspects of the body and evaluative aspects, while acknowledging that they interact" (p. 14), relating to embodiment and body image, respectively. In the blind person example, the cane acts as a prosthetic device which gets incorporated into the body as the boundaries of the self becomes ambiguous (MacLachlan, 2004). Thus, it would be interesting to explore if the same could be achieved for amputees adopting a prosthesis, and if so, highlight the necessary requirements for rehabilitation to achieve this (Murray, 2004).

A person receiving their first prosthesis is an important event, but whilst it may provide the feeling of completeness, there may also exist the issue of incorporation of an 'alien' object into the body schema (Van Lunteren et al., 1983). Thus, another dominant challenge in adjusting to limb loss or absence is embodiment of the prosthetic limb (Senra et al., 2012). *Prosthesis embodiment* (PE) involves feeling the prosthesis being 'part of' the user, becoming more than a mechanical object, having a psychological investment into the self (MacLachlan, 2004).

MacLachlan (2004) suggested a prosthesis could perceptually become part of a user to varying extents. Similarly, de Vignemont (2011) argues for different levels of embodiment for prostheses and tools, with incorporation (i.e., included within the body image) and extension (i.e., extending the body schema to include the tool), respectively. Indeed, tools can be embodied without ownership (de Vignemont, 2011). Prostheses can be considered as tools but are unusual tools, appearing as a body part, with the aim of replacement of the missing limb, rather than an extension (Gouzien et al., 2017). As mentioned previously, tool embodiment involves a change in body schema, however, this unconscious updating of limb position is distinguished from conscious body image perceptions (Longo et al., 2009). PE involves a change in body schema but also requires incorporating into the body image.

**2.5.5 Is embodiment of a prosthesis possible?** Support for the notion that a prosthesis can become embodied comes from brain responses to tools and prostheses, descriptions from amputees who have reported experiencing incorporation of their prosthesis, along with speculative and empirical observations by researchers. Clues towards the possibility of PE comes from brain imaging data associated with tool or prosthesis use. As previously mentioned, tools can become represented in the brain in regions of the cortex and other regions (the superior parietal lobe, inferior parietal lobule, cerebellum, ventral premotor cortex, dorsolateral premotor cortex, inferior frontal gyrus, and the somatosensory cortex) normally processing hand movements (Giummarra et al., 2008). Developing from this, Schmalzl, Kalckert, Ragnö, and Ehrsson (2014) conducted an experimental induction of embodiment of a rubber hand in amputees (this technique will be detailed in section 6.2.2.). They found that during embodiment of the rubber hand amputees displayed brain activation in areas associated with own-body perception. Further prosthesis-specific evidence, comes from a recent study suggesting PE occurs from prosthetic limbs recruiting neural resources originally devoted for hand function or body representation (Van den Heiligenberg et al., 2018). This study found PE was influenced by everyday usage of the prosthesis, with greater self-reported use of prostheses being positively correlated with greater brain activity in hand-specific visual areas after seeing prosthesis images.

Examples of personal descriptions of embodiment include one of MacLachlan's (2004) participants, who described anguish in discovering that her prosthetic legs needed to be replaced, and that this was more disturbing than losing her actual legs. This finding may indicate that she was experiencing anxiety in anticipation of the loss of her legs as if they

were a part of her body. Also, some of Saradjian et al.'s (2008) interviewees highlight their experience of the prosthesis integrating with their body image, having the consequent effect of the prosthesis partly existing outside of conscious awareness: "Dean: . . . over the years you just get used to them. It's just like a part of your skin." (p. 878) and "William: I've never thought of it. I just think that it's my arm." (p. 878). One of Murray's (2004) participants described how their prosthesis was part of them:

*Interviewer: When you say it's part of you now, what exactly do you mean by that?*

*Participant: Well, to me it's as if, though I've not got my lower arm, it's as though I've got it and it's [the prosthesis] part of me now. It's as though I've got two hands, two arms. (p. 970).*

Another amputee further elaborated on their sense of ownership of the limb:

*. . . many amputees feel that their artificial limb is somehow part of them, a simple example of this is that I wouldn't like just anyone putting their hand on my artificial knee, even though it is not actually part of my body's flesh, it is still mine even though it's a piece of plastic and metal. (p. 970).*

Personal reflections such as these highlight that the prosthesis can be included in areas of the body which we normally feel intimate ownership over, and offers a sense of completeness to the user (Murray, 2004).

Several researchers have suggested it is possible for the prosthesis to perceptually become part of the amputee (Murray, 2004). Empirical evidence for this comes from McDonnell (1988) and McDonnell, Scott, Dickison, Theriault, and Wood (1989), who found that from prolonged prosthesis use, amputees have an overestimation of how long their residual limb is, due to a gradual perceptual adaptation. It was suggested this could be an indicator of prosthetic limb incorporation with the body (McDonnell et al., 1989). Another potential indicator of incorporation was proposed by Fraser (1984), who identified the movement patterns of a successful prosthesis user, and found the prosthesis movements to be comparable to the anatomical limb movements. This was based on the assumption that embodiment of the prosthesis would result in more natural movement. Whilst Fraser's measure of incorporation is based on observations of behaviour instead of the phenomenal

experience of the user (Murray, 2004), this perhaps compliments the subjective accounts already mentioned, as another example of how a prosthesis can become part of the user.

Murray's (2004) qualitative study on the experience of perceptual embodiment of a prosthesis for successful users identified *The Prosthesis as Tool or Corporeal Structure* as one of the themes. This revealed that whilst some interviewees were able to embody the prosthesis as an extension to their body, others did not and experienced them purely as a tool that was used for practical purposes. For some participants in Saradjian et al.'s (2008) study, they compared it to like an item of clothing, for example: "Donald: I suppose it's like wearing glasses or what have you. You know, you choose a pair that are attractive that you think enhance rather than detract from your image and that you're comfortable with." (p. 878). Whilst the prosthesis served either an aesthetic or functional purpose for different interviewees, depending on the personal significance for each individual, it served a role for both for the majority of them (Saradjian et al., 2008). Similarly, on a broader level, despite some either adopting the prosthesis as an extension to their body or others simply using it as a tool, both affective and functional factors could be involved in PE (MacLachlan, 2004). Thus, as found with some interviewees, prostheses providing both aesthetic and functional roles could be incorporated into their body image, i.e., PE occurred (Saradjian et al., 2008).

**2.5.6 Encouraging prosthesis embodiment.** PE has been described as one of "two important milestones in the adjustment process" (Senra et al., 2012, p. 181), thus arguably an aim of rehabilitation (Murray, 2004). For example, Scarry (1994) reports that the medical community working with prosthesis users often talk of the need to transform the prosthetic limb from an 'inert supplement' or an 'extracorporeal structure' into a corporeal one (Murray, 2004, p. 964). Also, restoring a person's limb with a prosthesis, both acting and feeling like their own limb, is a significant aim of applied neuroscience (Collins et al., 2017). However, whilst some researchers suggest the prosthesis should feel part of the user (De Preester & Tsakiris, 2009; Moraal, Slatman, Pieters, Mert, & Widdershoven, 2013), the exact benefits of PE are often either not clearly defined, or simply assumed to exist. Evidence for such benefits will be discussed in the following sections.

## **2.5.7 Potential physical outcomes.**

**2.5.7.1 Increased prosthesis proficiency.** Several researchers have pointed out that a tool needs to be incorporated into the body to a certain degree to be used (Jain, 1999). Similarly, the potential influence of PE on prosthesis skill has been suggested by some researchers. For example, Wijk and Carlsson (2015) suggest that if an individual felt ownership of their prosthesis then functional improvements might be expected. Makin, de Vignemont, and Faisal (2017) also suggest improved PE could possibly increase intuitive control. Thus, PE is assumed by some to benefit proficiency with the prosthesis. A relevant analogy here is learning a new task with a tool, such as using a pencil (Churcher, 1984), where information (e.g., position of the hand) needs to be internalised for successful use as a bodily extension (Murray, 2004). Indeed, according to Van Lunteren et al. (1983) and Moraal et al. (2013), the naturalness of movements is largely determined by how well the prosthesis has been incorporated into the body schema. Moraal et al. support this with their case study of an amputee who progressively incorporated their prosthesis through Virtual Reality (VR) rehabilitation. This consequently led to a reduced conscious focus on his prosthesis, and developing an unconscious confidence in his bodily movements, both leading to more automatic movement. However, it is unclear whether this benefit was due to either incorporating the prosthesis, as a result of engaging in the VR rehabilitation, or both. Also, Moraal et al. reported that the prosthesis was incorporated with the participant's body but there was no mention of whether he consciously perceived the prosthesis as part of him.

Fraser (1984) considered that if a user's prosthesis was part of them, then prosthetic movement patterns might be expected to be comparable to the intact anatomical limb movements. Fraser found evidence for this. If embodiment results in more natural movement of the prosthesis, it could be expected that PE could lead to greater skill in use of the prosthesis. However, as Murray (2004) highlights, PE in Fraser's study was based on observations of behaviour, so it is unclear whether PE was present. Also, the assumption of the link between embodiment and movement patterns can be questioned, as comparable patterns of movement may not be necessary for the feeling of PE (Murray, 2008). Murray (2008) provides the example of tool use (e.g., use of a cane by a blind person), where artefacts are not anatomical in nature, yet can still be embodied. Additionally, the physical constraints of prostheses might limit their ability in matching that of an anatomical limb, despite PE. Despite it being impossible to move prostheses in an entirely 'natural' manner, it

is suggested the integration of a prosthesis into a person's body schema is related to their feeling of having control over their body which Christ et al., 2012 suggest, might improve prosthesis movements. However, Christ et al. do not provide specific empirical evidence for this notion.

If PE encourages heightened prosthesis skill, a potential 'side-effect' might be increased use, as there is an expectation that improved functionality leads to a greater use of a prosthesis (Dietrich et al., 2012). It should be noted, however, that this is an assumption not based on direct evidence. Also, one participant in Wijk and Carlsson's (2015) study reported "If I had a prosthesis that did what I want, then of course I would have been a full-time prosthesis user." (p. 273). Whilst this might relate more to prosthesis satisfaction, the sentiment can also be applied to greater skill in controlling the prosthesis causing a greater use of the prosthesis. However, a relationship between satisfaction with abilities and use was not found in one study (Davidson, 2002), suggesting that greater skill, rather than perceived satisfaction of an individual's level of skill, might relate to greater use.

**2.5.7.2 Increased prosthesis use.** As noted in the previous section, PE could have an indirect influence on prosthesis use, as encouraging prosthesis skill could naturally lead to greater prosthesis use. In addition, PE may have a direct influence on use due to the limb feeling part of the user, and thus encouraging more natural and regular use of it. Incidentally, Makin et al. (2017) note that clinicians and engineers have considered that rejection of a prosthesis can happen due to the limb not feeling as a body part; however, this consideration is currently an untested assumption. As previously mentioned, a prosthesis may be seen by its user as useful for some activities, whereas for others it may not (Murray, 2009), hence may only be used for particular tasks, or not used at all, because of its perceived limited use overall. However, PE could increase the chance the prosthesis is used for a greater number of activities. For example, some wearers of active prostheses only use it like a cosmetic prosthesis in social situations, ignoring the prosthesis's active capabilities available to them (Biddiss & Chau, 2007b). In this example, if the limb felt as part of the user, they might naturally make more use of the active functions of the prosthesis in social situations, thus increasing their prosthesis use overall.

Aside from increased prosthesis skill, another possible indirect influence on prosthesis use, as a result of PE is reduced awareness. Moraal et al.'s (2013) participant's reduced

awareness enabled them to ignore problems in moving the prosthesis; this, combined with confidence in their body, could increase the likelihood the prosthesis would be used. Additionally, improved body image might influence prosthesis use, as problems with accepting body image can lead to prosthesis rejection (Racy, 2004), suggesting a link between body image and use. However, Racy does not provide evidence for the proposition of body image issues leading to rejection, just referring to a personal communication. Also, a more positive body image has been found to be related to less functional restriction (Gallagher et al., 2007) and greater participation in physical activities (Fisher & Hanspal, 1998; Wetterhahn et al., 2002). These 3 findings were based on correlational statistics, possibly suggesting a positive body image enables the individual to feel less restricted in movement or function, and hence encouraging prosthesis use. However, as Mayer et al. (2008) note, those amputees who engage in physical activity have a more positive body image, which could suggest physical activity (including greater prosthesis use) improves body image.

Greater prosthesis use would be beneficial as, similar to skill, this is a main aim of rehabilitation to help the user achieve a successful functional outcome. Prosthesis use should lead to an improved body image (Saradjian et al., 2008; Wetterhahn et al., 2002) and is associated with an improved quality of life (Gallagher & MacLachlan, 2004). Greater use should also encourage development of skills in using the prosthesis, and increased prosthesis satisfaction, suggested by the relationship found between use and satisfaction (Bilodeau et al., 2000; Davidson, 2002). However, cause and effect or the direction of the relationship cannot be determined, as it is also possible that increased satisfaction leads to further use.

## **2.5.8 Potential psychological outcomes.**

**2.5.8.1 Improved body image.** Studies highlight that prosthesis wearing has significant importance for body image restoration (e.g., Saradjian et al, 2008). In addition, PE involves incorporating the prosthesis into the user's body image representing a previously experienced 'complete' form (e.g., for amputees), or a form considered more acceptable by society (e.g., for those with congenital limb absence). Thus, in either case, an improved body image might be expected, having consequent psychosocial benefits for the user. However, the link between PE and an improved body image has not been directly explored by previous research.

As body image is related to psychosocial wellbeing (previously detailed in section 3.2), assessment of an amputee's body image during rehabilitation and encouraging body image to be more positive would be beneficial (Breakey, 1997). Flannery and Fariah (1999) agree, noting that the direct relationship between losing a limb and its impact on a person's body image highlights the need to manage this impact by health care professionals. However, the authors only detail limb loss being conceptually linked to having an altered body image. They suggest, through perceiving their body differently, an amputee becomes preoccupied with thinking about their new body image. Rybarczyk et al. (2004) highlight that body image disturbance is important for predicting a patient's rehabilitative outcome and could be a significant intervention area to explore. The authors refer to research evidence supporting this notion (e.g., body image predicting, depression, quality of life, and prosthetist ratings of amputees' psychological adjustment, Rybarczyk et al., 1995). Racy (2004) further argues that integrating a prosthesis into a person's body image is one of the critical elements to achieve prosthetic rehabilitation. Thus, PE could be both important for rehabilitation and could be expected to have a positive impact on body image by restoring a sense of 'completeness' for the person.

Aside from the psychological benefits of a positive body image, improving body image could have three potential positive outcomes - prosthesis use, participating in physical activities, and prosthesis skill. For the former, as previously detailed, there are research findings (previously detailed in section 5.7.2.) suggesting a more positive body image could influence use (Racy, 2004), functional restriction (Gallagher et al., 2007), and participating in physical activities (Fisher & Hanspal, 1998; Wetterhahn et al., 2002). Also, the greater prosthesis satisfaction found to be associated with positive body image (e.g., Breakey, 1997; Murray & Fox, 2002) could naturally lead to an increased use of the prosthesis, although the direction of these and the above relationships is unclear.

**2.5.8.2 Reduced awareness of the prosthesis.** Another potential outcome of PE is a reduced awareness of the prosthesis. Supporting this, integration of the prosthesis with a user's body image was found to have the consequent effect of a reduced awareness of the prosthesis in Saradjian et al.'s (2008) study and Moraal et al.'s (2013) case study. Additionally, if the prosthesis is internalised in an equivalent manner to using a tool



(Churcher, 1984), i.e., incorporated into the body schema as an extension of the body, this can result in the loss of focal awareness of the prosthesis (Murray, 2004).

A reduced conscious awareness would be beneficial, as the user would experience the prosthesis in a similar way to their anatomical limb (i.e., no greater attention drawn to their prosthesis than that of their intact or previous arm). This, could potentially encourage more natural movement involving a greater automaticity in use of a prosthesis. The extent of these outcomes might be represented by the degree in which the user either focuses on their behavioural goal or on their prosthesis (Mills, 2013), with the former highlighting the potential consequence of a more natural use of the prosthesis. Support for this comes from some of Murray's (2004) interviewees, who related a higher level of awareness to more unnatural use of their prosthesis. Further support comes from Moraal et al.'s (2013) case study participant, whose acquired automatic movement was attributed to both a reduced focus on the prosthesis, and increased confidence in bodily movement. Further to these points, if the prosthesis does not feel part of the body then a heightened awareness of the prosthesis, beyond that naturally experienced with an anatomical limb, might be expected.

**2.5.9 Factors influencing prosthesis embodiment.** Rognini et al. (2018) highlight there is a goal of combining neuroscience with prosthetics in designing a prosthesis that is embodied like a real limb. They note, however, that, despite advancement of technology, this goal is currently not achieved, with such embodiment provided by prosthetic limbs being limited (Rognini et al., 2018). Thus, understanding the factors that influence the occurrence of PE would be beneficial. See Table 1 for a summary of the factors influencing PE. These will be detailed further in the following sub-sections.

Table 1

*Summary of factors influencing prosthesis embodiment*

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Embodiment factors
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Phantom limbs
Amount of prosthesis use
Sensory feedback
Length of time with prosthesis
Type of prosthesis
Awareness of prosthesis
Satisfaction with prosthesis
Body image

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**2.5.9.1 Phantom limbs.** The presence of a phantom limb, although often distressing, can also sometimes help in adjusting to a prosthetic limb. This was highlighted in one of Murray's (2004) main themes, *The Phantom Becomes the Prosthesis: Extending the Body*, identified in his qualitative study. Here, phantom limbs appeared to be associated with experiences of the prosthesis becoming part of the user's phenomenal body. For some, the phantom was spatially incongruent with the prosthesis to the extent that it was almost impossible for them to adopt the same position, whereas for others they formed a phenomenal corporeal structure (Murray, 2004). The impact of the latter is highlighted in the following quotes from amputees' experiences: "It is certainly nice to still feel the [phantom] foot. Primarily, it facilitates the use of the prosthesis because I don't feel as anything is really missing. So my prosthesis is 'natural'" (p. 969) and "Well, in a way, the prosthesis is the visual manifestation of the phantom arm. In other words [ . . . ] it merely provides something tangible which represents the imaginary" (p. 970). These show that the correspondence of both the phantom and prosthetic limb results in the former aiding the use of the latter. How the phantom manifests as prosthesis and facilitates bodily function, in this case walking, is elaborated here:

*When I put on a prosthetic, the phantom becomes the prosthesis to the extent that the notfoot [phantom] is in almost the same position as the Flexfoot [a brand of prosthesis], maybe slightly more rotated. The fit is so good, that it makes walking with the prosthesis easier because of the correspondence between the prosthetic leg and the phantom. (p. 970)*

Evidence supporting these qualitative accounts comes from the finding of PE being more common in a sample of participants with a phantom limb in a more natural position (i.e., spatially congruent with the prosthesis) than those with a telescoped phantom limb (Giummarra et al., 2010). Such accounts highlight if it was possible to manipulate the position of a phantom limb to be spatially congruent with the prosthesis, so that they formed a corporeal structure, this could be beneficial for rehabilitation. Niedernhuber, Barone, and Lenggenhager (2018) highlight that further support for the potential influence of spatial position of the phantom limb, is evidence from experiments with healthy participants incorporating an artificial body part. The researchers suggest that alignment between a phantom limb and prosthesis may be needed for incorporation of the prosthesis to occur.

**2.5.9.2 Sensory feedback.** It is suggested that PE is more likely if feedback is experienced as coming from the interface between the environment and the prosthesis, compared to the interface between the prosthesis and the user's residual limb (Mills, 2013). Tactile feedback normally received through the skin from interacting with objects is usually missing in prostheses. The sense of touch is an important hand function, and loss of sensory function is barely compensated for by hand prostheses, with no commercial prosthesis providing sensory feedback via touch (Wijk & Carlsson, 2015). Despite this, some vibrotactile feedback can be provided to the residual limb and with myoelectric prostheses, auditory feedback from the motors (Rooks, Vogel, & Fleming, 1993). Whether sensory feedback leads to PE will depend on the type of prosthesis and how it is physically integrated with the residual limb (Mills, 2013). For example, Mills suggests *osseointegrated* (anchored via the bone) prostheses appear to provide more vivid feedback compared to socket technology. Support for this suggestion is provided by osseointegrated prosthesis users reporting their prosthesis feeling more part of them in comparison to a socket-suspended prosthesis (Hagberg, Häggström, Jönsson, Rydevik, & Brånemark, 2008), for example in a qualitative study where users directly compared the two types of prosthesis (Lundberg, Hagberg, & Bullington, 2011). An example of experiencing feedback from the prosthesis interacting with the environment, is from one of Murray's (2004) interviewees, a lower-limb amputee who could sense the ground via their prosthesis. Murray notes this is an example of incorporation of the prosthesis into bodily space becoming an extension of the body, however it is unclear if this interviewee reported feeling PE. Clarifying this point, in Wijk and Carlsson's (2015) qualitative study, sensory feedback from prostheses was found to contribute to ownership and embodiment of the prosthesis.

**2.5.9.3 Type of prosthesis.** Evidence suggests that purposeful use of a tool extends the arm within the body schema (Giummarra et al., 2008). One way to assess an individual's body schema is to measure the extent to they are able to imagine moving different parts of their body (motor imagery). Amputees who use a cosmetic prosthesis, without motor function, are less able to perform motor imagery of the hand, implying that incorporation into the body schema only occurs for functional prostheses (Nico, Daprati, Rigal, Parsons, & Sirigu, 2004). The implication, therefore, is that the type of prosthesis could have an influence on PE based on its functional capabilities. Despite the implication of cosmetic prosthesis not being incorporated into the body schema, such prostheses could still be used to carry out activities, albeit to a lesser extent than functional prostheses. Also, others factors could play a role in PE, meaning embodiment may still occur for those using a cosmetic prosthesis, for example incorporation of the prosthesis into the user's body image.

**2.5.9.4 Satisfaction with prosthesis.** It is suggested by Saradjian et al.'s (2008) qualitative study that for users, prostheses serving both facilitation of appearance and function, has an influence on the prosthesis integrating into the body image. Thus, PE was occurring. However, the relative importance of this for individuals will vary, so subjective satisfaction with the prosthesis may influence embodiment.

**2.5.9.5 Amount of prosthesis use.** Repeated prosthesis use leads to an innate sense of proprioception being extended to include the prosthesis as if it were part of the body (Giummarra et al., 2008). This was found by Mayer et al. (2008), with the configuration of body schema for amputees being affected by amount of prosthesis use. Thus, it might be suggested that the more a prosthesis is used, the greater chance of it being incorporated into the person's body schema, similar to how a tool is embodied (Giummarra et al., 2008). Supporting use leading to incorporation, is the finding of the end of the residual limb being perceived to be further due to prosthesis use (McDonnell, 1988; McDonnell et al., 1989). However, this finding does not necessarily suggest subjective feelings of PE would be encouraged. MacLachlan (2004) notes that perceptual aspects of the body (e.g., perceptions of body boundaries) may interact with evaluative aspects (e.g., thoughts and feelings about the body) of the body image, but this is currently unclear.

**2.5.9.6 Length of time with prosthesis.** Long-term use of prostheses has been found to influence PE (Mayer et al., 2008; Murray, 2004; Murray, 2008). Length of use may have a subtly different influence on PE than amount of use because with at least some use of the prosthesis, the user may gradually adapt to their prosthesis over a long period of time. An example of this, is quote from one of Saradjian et al.'s (2008) interviewees, presented earlier - "Dean: . . . over the years you just get used to them. It's just like a part of your skin." (p. 878). However, whilst length of time with a prosthesis might afford a greater amount of overall use, if a user owns their prosthesis for a long time but hardly uses it at all, it is not expected to result in PE. Additional support for length of time influencing PE, is that length of time with the prosthesis could naturally correspond to time since amputation if the prosthesis was received soon afterwards. Time since amputation has been found to positively correlate with adaption to both amputation (i.e., psychological adjustment) and a disrupted body image (Horgan & MacLachlan, 2004), which could also play a mediating role in the effects of time with prosthesis on PE.

**2.5.9.7 Awareness of prosthesis.** Mills (2013) argues that 'transparency', the absent awareness of the body part (ranging from background disappearance/marginal awareness to focal disappearance) is required for the prosthesis to be incorporated. An example of this, is a proper fitting of both components to the socket, and socket to residual limb, is needed for transparency; otherwise discomfort or pain will likely result in the feeling of just a tool attached to the body (Mills, 2013). From interviewing users, Saradjian et al. (2008) suggested that integration of a prosthesis to a user's body image meant the prosthesis was largely absent from their conscious awareness. Thus, it could be argued the level of overall conscious awareness a user has of their prosthesis (e.g., in general, or when performing activities) may influence whether PE occurs (i.e., with low awareness or high awareness encouraging or hindering PE, respectively).

**2.5.9.8 Body image.** Body image disturbance has been found to predict psychological adjustment to amputation (Rybarczyk et al., 1995; Rybarczyk et al., 2004). Similarly, body image alterations are an important issue in influencing prosthesis acceptance (Rybarczyk & Behel, 2008), along with higher body image disturbance being related to lower prosthesis satisfaction (Breakey, 1997; Gallagher et al., 2007; Murray & Fox, 2002). This possibly suggests that a more positive body image could encourage satisfaction and acceptance of the prosthesis. Similarly, the individual level of body image disturbance, may impact PE. Body

image has a close relationship with body schema (Mills, 2013) and it can be argued that aspects of PE involve incorporating the prosthesis into both the user's body image and body schema. Thus, it seems possible that the individual's feelings towards their body before use of the prosthesis could have an impact on the likelihood of PE occurring.

## **2.6 Studies designed to influence embodiment**

The following section will discuss techniques used to explore aspects of embodiment, including inducing ownership of a non-body part, an equivalent effect in virtual reality, and extension of body-part ownership techniques to ownership of a full body. The section will then discuss how such techniques have begun to be adapted for amputees and implications for embodiment of prostheses.

**2.6.1 Body ownership techniques.** A commonly used body ownership method is a bodily illusion, the *rubber-hand illusion* (RHI; Botvinick & Cohen, 1998). This traditionally involves a tactile stimulus (e.g., feeling paintbrush strokes) applied to a participant's hand hidden from view, synchronised with a visual stimulus (i.e., seeing paintbrush strokes) applied to a rubber hand in front of them. For some, this causes the feeling of ownership over the rubber hand, and the location of the real hand is perceived to be closer to the rubber hand (*proprioceptive drift*). If the stimulation is *asynchronous* (i.e., stimulation of the rubber and real hand is out of sync) then the illusion is absent or significantly reduced (Shimada, Fukuda, & Hiraki, 2009). The responses to this are measured using self-report questionnaires (measuring feeling of ownership and agency), proprioceptive drift (measuring the perceived position of the stimulated hand), or physiological response (e.g., skin conductance) to a threat to the rubber hand. Research has shown the RHI depends on bottom-up processes of sensory stimulation (e.g., synchrony of stimulation) interacting with top-down processes relating to body schema (e.g., hand shape, Tsakiris & Haggard, 2005).

Evidence suggests it is possible to embody non-human looking robotic arm using the RHI (Aymerich-Franch, Petit, Ganesh, & Kheddar, 2017). In their study, participants' hands were stroked synchronously with a robotic arm, either with the arm either ending with no fingers or a gripper. Perception of the robotic arm was presented via a head-mounted display (HMD) displaying a real-time video feed focused on the arm from the perspective of the robot. Embodiment was found to be comparable between the robotic hand and a human-

looking hand control condition. Aymerich-Franch et al. also explored the impact of visuo-movement stimulation, i.e., the participant moving their real hand in synchrony with the robotic hand moving. This was achieved via camera-captured movement tracking and robotic arm movement technology and found embodiment also occurred using this technique. This study has direct relevance for the below paragraphs on using HMDs to either induce embodiment of a virtual hand or a full body.

The RHI has been replicated using Immersive Virtual Reality (IVR, e.g., Perez-Marcos, Slater, & Sanchez-Vives, 2009; Slater, Perez-Marcos, Ehrsson, & Sanchez-Vives, 2008, 2009; Yuan & Steed, 2010) and non-immersive VR (e.g., Hågini et al., 2008). VR applications of the RHI are referred to as the virtual-hand illusion (VHI). The VHI involves stimulation to a participant's real hand while they are presented with corresponding visual stimulation applied to a virtual hand, presented either on a HMD, screen projection, or PC monitor.

This technique has also been extended to a full-body illusion (FBI) using either IVR or a specific camera set-up (e.g., Ehrsson, 2007; Ionta et al., 2011; Lenggenhager, Tadi, Metzinger, & Blanke, 2007; Lenggenhager, Mouthon, & Blanke, 2009), creating the illusion of either a person's self-location being spatially separate from their body, or inside another bodily form (e.g., a mannequin or virtual avatar). These alterations of bodily form further show how a basic synchronised visuo-tactile stimulation can construct or manipulate feeling of body ownership.

The clinical benefits of these techniques have begun to be explored. For example, a VHI within IVR was found to increase pain threshold (Martini, Perez-Marcos, & Sanchez-Vives, 2014), i.e., feeling ownership over another body reduced experience of pain over the person's actual body. Additionally, an emerging area of research is exploring the 'carry over' effects of the FBI within IVR, in order to explore the potential applied benefits of this technique. For example, Preston and Ehrsson (2014) manipulated perception of body size and found this influenced both perception of actual body size and body satisfaction, along with finding a potential link to eating disorders. Furthermore, Serino et al. (2016) found that VR 'body swapping' (i.e., experiencing a different virtual body) manipulated the person's own-body memory.

In addition to the above techniques, electrical brain stimulation has been used to encourage embodiment. Collins et al. (2017) induced ownership of a rubber hand by combining visual stimulation of the hand with stimulation of part of the somatosensory cortex relevant for hands. Notably, ownership of a rubber hand was not induced with asynchronous stimulation or stimulation to a part of the cortex representing a different body part. The researchers suggested this further shows that the central mechanism of the RHI is multisensory integration, based on the congruency of spatial and temporal factors. Another form of stimulation has also been used to encourage embodiment is non-invasive *transcutaneous electrical nerve stimulation* (TENS). TENS involves skin-surface stimulation of nerves via electrical currents, which induces a perception of electrical *paraesthesiae* (Mulvey, Fawkner, Radford, & Johnson, 2009). Studies using a modified RHI found it was possible for TENS paraesthesiae to be experienced as originating from a rubber hand, and this facilitated embodiment of the hand (Mulvey et al., 2009; Mulvey, Fawkner, Radford, & Johnson, 2012). The researchers suggested such a technique could potentially help encourage PE via integrating the limb into an amputee's body schema.

## **2.6.2 Applying bodily illusions for amputees.**

**2.6.2.1 Mirror box therapy.** Mirror box therapy (e.g., MacLachlan, McDonald, & Waloch, 2004; Ramachandran & Rogers-Ramachandran, 1996) was developed to reduce phantom limb pain (PLP), where an intact limb placed in a box is reflected by a mirror where the amputated limb should be. Moving the intact limb creates the visual feedback of the phantom limb moving, which can reduce pain for some (Desmond, O'Neill, De Paor, McDarby, & MacLachlan, 2006). A study by Giummarra, Georgiou-Karistianis, Nicholls, Gibson, and Bradshaw (2010) combined RHI and mirror box methods, which found amputees could embody a rubber hand which was being stimulated and reflected in a mirror in the position where their phantom was. Of note, this study also found that ownership was also possible without any stimulation (e.g., paintbrush strokes) presented to the rubber hand; the effect only required the rubber hand reflected in the mirror spatially coinciding with the amputee's phantom hand. In addition to this, when the rubber hand was stimulated, 79% of amputees experienced illusory sensations in their phantom hand.

The mirror box design has since been adapted for augmented reality (AR; e.g., Desmond et al., 2006) and IVR, by having amputees wear a tracking glove with sensors on



their intact hand which transfer to the opposite virtual arm, representing the missing limb (e.g., Murray, Patchick, Pettifer, Caillette, & Howard, 2006). The use of IVR for such therapy is useful because there are methodological constraints in using the traditional mirror box (Desmond et al., 2006). Despite the benefits of the VR mirror box therapy, this is itself constrained as only benefits unilateral amputees and ignores the actual effort involved in phantom limb motion (Ortiz-Catalan, Sander, Kristoffersen, Håkansson, & Brånemark, 2014). To counter this, Ortiz-Catalan et al. measured myoelectric activity from an amputee's stump, which was used in real time to control an AR-restored hand and arm (via predicted pattern recognition). Whilst only including a single amputee, the findings have importance for rehabilitation, as both PLP and telescoping were reduced, the phantom limb previously characterised as a tightly clenched fist assumed the neutral position of the virtual hand, and the phantom became freely movable. Also, whilst embodiment was not explored, this technique could effectively be used as a method to explore PE in a RHI-paradigm, which leads to the following section.

**2.6.2.2 Body ownership techniques for amputees.** Ehrsson et al. (2008) created a RHI for amputees by synchronous stimulation of a rubber hand and the end of the residual limb. This technique is achieved via previously identified referred sensations from the stump to specific parts of a phantom hand, termed as 'mapping of the phantom hand/stump mapping' (Ehrsson et al., 2008; Schmalzl et al., 2011). In Ehrsson et al.'s study, there was a RHI effect for the group overall (based on questionnaire responses) and a strong sense of ownership occurred for 33% of participants, suggesting the potential for PE. Further supporting the potential of using such a technique for inducing PE, the protocol was replicated for a robotic hand (Rosen et al., 2009), showing that hands can appear different to biological hands (Niedernhuber et al., 2018). Despite these findings, Ehrsson et al. note that there was a weaker and less vivid illusion for amputees compared to the traditional RHI, which was tested in the group with their contralateral hand.

**2.6.2.3 Full-body illusion.** Following on from Ehrsson et al. (2008)'s study, research by Schmalzl et al. (2011) explored manipulation of the spatial position of phantom sensations using the same amputee-RHI techniques. As previously mentioned, for some, phantom limbs can be spatially incongruent with the prosthesis and sometimes be telescoped inside of the stump. This is clinically relevant as telescoping is usually associated with increased levels of PLP (Schmalzl et al., 2011). Only those with telescoped phantom limbs were included in

Schmalzl et al.'s study, suggesting they might suffer from high levels of PLP and potentially benefit from the study. The experiment involved a FBI protocol, with an amputee wearing a head-mounted display (HMD) showing a first-person perspective of a mannequin's body, via a camera feed on the mannequin's head. This was based on an earlier 'test of principle' study using non-amputees with a mannequin missing its lower arm (Schmalzl & Ehrsson, 2011). This previous study had the aim of seeing whether a FBI was possible with an 'incomplete' body and whether telescoping-type sensations could be induced in non-amputees. The study found both of these effects were possible (Schmalzl & Ehrsson, 2011).

For amputees in Schmalzl et al.'s (2011) study, a FBI was induced with both a complete mannequin, and one missing its lower arm matching the amputee, using the RHI stump mapping procedure. In the incomplete condition, with the mannequin's lower arm missing, paintbrush strokes were applied to either the empty space below the mannequin's stump (i.e., where the hand should be), or the stump itself. For both conditions, depending on the location of brushstrokes, participants either experienced their phantom hand inside the stump or below the stump/where the mannequin's hand was. In the latter situation, this was associated with a reduction of PLP for some (Schmalzl et al., 2011). This suggests a potential alternative rehabilitative method than mirror box therapy. Whilst only preliminary evidence, Schmalzl et al. argue it provides a rationale for further research with a larger sample exploring the impact of illusory movement of the phantom limb on PLP.

Follow-up research to Schmalzl et al.'s (2011) study highlighted that such body ownership techniques could also potentially help those whose pain was either resistant to, or increased by, traditional mirror box therapy (Schmalzl, Ragnö, & Ehrsson, 2013). In mirror box therapy the experienced movement of a phantom limb normally leads to reduced pain, however for some this leads to increased cramping sensations (Schmalzl et al., 2013). The researchers proposed that their body ownership protocol, combined with a mirror box therapy setting, could help those whose pain increased due to the phantom movement. Indeed, Schmalzl et al. (2013) found that those who did not benefit from traditional mirror therapy experienced a significant reduction of PLP with their body ownership method. It was concluded that individual differences in phantom sensations could directly relate to the type of mirror box therapy that is successful in reducing PLP. More specifically, the standard mirror box type of movement could allow for phantom limbs locked in space to move again and stop clenching sensations. Alternatively, the body ownership technique could help those

who have natural movement of their phantom but with associated heightened cramping sensations (Schmalzl et al., 2013).

**2.6.2.4 Implementing body ownership techniques into prosthetics.** Ramakonar, Franz, and Lind (2011) suggest applying understanding from the RHI to exploring ownership of prosthetics. In considering the implementation of embodiment of prostheses, Christ et al. (2012) highlight the need to maintain the feeling of ownership of the prosthesis, so that the tactile stimulation used in the RHI is not needed to be constantly applied from the prosthesis to induce embodiment. They argued for a need to understand how movement influences the RHI, with their systematic review finding that movements can also induce embodiment. The authors also differentiated between active (i.e., self-generated) and passive movement (i.e., externally-generated), with agency only involved with active movement, but the RHI possible with both passive and active movement.

Despite Christ et al.'s (2012) suggestions, recent research is exploring the use of RHI techniques to provide sensory feedback to the stump in specially adapted prostheses (Antfolk et al., 2012; Berg et al., 2013; Crea, D'Alonzo, Vitiello, & Cipriani, 2015; D'Alonzo, Clemente, & Cipriani, 2015; Hellman, Chang, Tanner, Tillery, & Santos, 2015; Liu, Yang, Jiang, & Fan, 2014; Marasco, Kim, Colgate, Peshkin, & Kuiken, 2011; Rognini et al., 2018). It is suggested that TENS may be useful in facilitating the incorporation of a prosthesis into an amputee's body schema (Mulvey et al., 2009). The lead researcher and other researchers supported this by finding that sensations from TENS could be projected to phantom sensations in amputees, with sensations feeling as if arising from a prosthesis (Mulvey et al., 2013). However, for use in encouraging PE, they note a feasibility study including a placebo TENS control condition is needed. Furthermore, Chai, Sui, Li, He, and Lan, (2015) explored the stability of the projected finger map (i.e., specific parts of a phantom hand experienced via stimulation of parts of the stump) and sensory threshold of evoked tactile sensations, by applying TENS to 11 amputees' stumps. Their findings supported the suitability of using a non-invasive neural interface (i.e., a system connecting prosthetic feedback with nerve stimulation without the need for surgery) within the prosthesis, with tactile feedback that is specific for each finger. Development of prosthetics implementing this particular use of TENS has begun (e.g., Liu et al., 2014).

In a similar application as TENS, D'Alonzo et al. (2015) explored the use of modality-mismatched stimulation (the combination of two different types of stimulation, e.g., vibration and paintbrush strokes) in a RHI-paradigm. The experiment involved referred sensations of amputees' phantom limbs to a rubber hand, via vibrotactile stimulation of the stump, and paintbrush strokes, respectively. This *sensory substitution* still facilitated embodiment of the hand. The researchers suggested their findings could avoid the physical constraints of applying the combination of touch sensors and haptic tactile stimulators in a prosthesis. Instead, allowing for the possibility of small vibrators fitted into standard prostheses, inducing embodiment each time an object is touched. Another technique of applying sensory feedback to prostheses is direct peripheral nerve stimulation, which induces somatosensory perception of the phantom limb (Tyler, 2015). A recent study combined tactile sensations on a phantom limb, via peripheral nerve stimulation, with visual illumination feedback superimposed on a prosthesis from HMD-facilitated AR (Rognini et al., 2018). The visuo-tactile neural stimulation induced both PE and reduced telescoping of the phantom limb. Whilst the study only included 2 amputees, it further highlighted the potential for encouraging PE, reduction of telescoping, and the potential use of exploring prosthetics in IVR.

**2.6.3 Prosthesis use in VR.** Christ and Reiner (2014) highlight possible applications of a RHI combined with VR for rehabilitation. One such area could be to attempt to encourage PE. Current research applying RHI techniques directly to prostheses would require a specially adapted prosthesis, possibly only suitable for certain types. Thus, exploring the use of such techniques in IVR could be beneficial in providing an alternative, more flexible method, potentially useful for any prosthesis type. The use of body ownership techniques applied to prosthetics in VR could serve two different approaches. One approach involves exploration of factors that naturally influence PE using a VR prosthesis simulation. The other approach is exploring whether it is possible to encourage PE for amputees or those with congenital limb absence using such techniques as a form of therapy or intervention. Supporting this, is the increasing recognition of the benefits VR can provide for rehabilitation (e.g., Bohil, Alicea, & Biocca, 2011; De Mauro, 2011; Holden, 2005; Sveistrup, 2004; Wilson, Foreman, & Stanton, 1997). However, the intervention approach would need to first develop a robust protocol, with PE measured in an experimental context. Then, it would need to explore carry-over effects from the VR-protocol to a user's own prosthesis. This approach, however, is constrained by requiring a large sample and longitudinal testing of the

effectiveness of the techniques for encouraging PE in a user's own prosthesis (including the persistence of any effects).

Prostheses have been utilised within VR in a variety of areas. One area is the use of VR simulations to aid optimisation and development of prostheses (e.g., Hauschild, Davoodi, & Loeb, 2007; Lambrecht, Pulliam, & Kirsch, 2011; Resnik, Fantini, Disla, Etter, & Klinger, 2011). Research has also explored prosthesis training using VR (e.g., Hauschild et al., 2007; Lambrecht et al., 2011; Phelan, Arden, Garcia, & Roast, 2015; Pons et al., 2005; Resnik, et al., 2011) and AR (e.g., Boschmann, Dosen, Werner, Raies, & Farina, 2016), highlighting the importance of experiencing a first-person perspective body in VR, with similar implications for embodiment studies. Moraal et al. (2013) reported an amputee case study using VR rehabilitation, which had a significant psychological and functional effect on the participant. These studies highlight the use of VR in the area of prosthetics, through development of, prior training with, and rehabilitation of prostheses.

Whilst not specifically using prosthetics, Ortiz-Catalan et al. (2014) incorporated myoelectric activity measured directly from a single amputee's stump, corresponding this with a restored arm in AR. The study found that PLP and telescoping were reduced, along with the user being able to move their phantom limb, which was previously locked in place. However, the focus of this study was on reducing PLP, as with the related VR-induced mirror-box studies. The study also did not involve an immersive protocol from a first-person perspective as the participant simply observed a reflection of themselves on a PC monitor. These limitations were improved upon in similar studies by Snow, Sedki, Sinisi, Comley, and Loureiro (2017) and Chau et al. (2017). Both involved an IVR first-person perspective, with a virtual hand controlled by a robotic system. In the former study, and myoelectric arm band in the latter study. Additionally, Snow et al.'s study incorporated haptic feedback from interaction with virtual objects and measured embodiment. This and Chau et al.'s study involved the element of agency controlling a virtual limb on the same side as the amputated limb. Both studies found that PLP was reduced as a result of the intervention. Additionally, in Chau et al.'s study the amputee's phantom hand moved from a clenched to normal position along with the person reporting a subjective experience of embodiment. There is also some suggestion from Snow et al.'s study that increased embodiment can influence reduction of PLP.

Such EMG-controlled virtual hand studies are important and relevant for prosthesis users; however, they notably were involving a normal arm resembling an intact limb rather than prosthesis. Also, only Ortiz-Catalan's study involved the virtual arm being attached to a body (in this case, the participant's actual body), with the other studies having disembodied hands or arms. This is relevant because the perceived connectedness between a virtual hand with a body has been shown to impact upon feelings of ownership and skin conductance responses to a threat (Tierì, Tidoni, Pavone, & Aglioti, 2015).

## **2.7 Rationale for the proposed research**

The following section will detail the rationale for the thesis as a whole, in terms of the need for understanding the factors which influence PE. This is based upon previous work which has begun to develop understanding of the potential importance of embodiment of a prosthetic limb. It is clear that in order to identify whether a prosthesis becomes embodied or not, or to what level of embodiment is achieved, a broad range of psychological and physical factors need to be considered. The section will argue for various approaches to answer such questions, including in-depth qualitative interviews to identify the complexity of PE, survey techniques focus on the factors most relevant for PE, and the use of virtual reality to experimentally explore specific factors and their potential impact on PE.

**2.7.1 Prosthesis embodiment.** Whilst physical problems with using prostheses (e.g., physical effort and discomfort) can lead to prosthesis rejection, these may be potentially reduced through prosthesis users persevering with their prosthesis, leading eventually to more automatic use (Murray, 2004). The question remains whether embodiment can provide a similar effect of 'pre-reflective' use that could lead to a greater amount of prosthesis use and/or skill. Additionally, if PE improves body image, this could have psychological benefits for prosthesis users, in terms of increased quality of life and help towards protecting against depression. Improving body image could also consequently encourage prosthesis use. Ultimately, PE may have a significant influence on whether a prosthetic limb is persevered with. It is not possible to directly test this in the current research study, however, if the relationship between PE and the above benefits can be established, then future research may be able to directly explore the impact of PE on prosthesis rejection.

Some researchers have proposed that a prosthesis user should incorporate the prosthesis as part of them and this is arguably an aim of prosthetic rehabilitation (De Preester & Tsakiris, 2009; Dhillon & Horch, 2005; Moraal et al., 2013; Murray, 2004; Van Lunteren et al., 1983). More specifically, it has been suggested that PE may be related to a person's decisions regarding wear and use of a prosthesis, thus encouraging embodiment could be beneficial for rehabilitation. In order to help facilitate PE, the factors influencing its occurrence need to be understood.

Due to the complex nature of the above outlined factors, applying a mixed-methods design to this thesis, was deemed to be beneficial. The thesis includes a qualitative interviews study focusing on furthering understanding of embodiment, a survey study with a larger group of prosthesis users to explore potential factors identified during interviews, along with experiments in IVR using body ownership techniques to encourage embodiment and test various influences on this process.

**2.7.2 Qualitative study on factors associated with embodiment.** Previous research has established that prosthesis users report different embodiment experiences. For example, Murray (2004) identified that some users report feeling their prosthesis was a part of them body, whilst others reported it as feeling more like a tool. An outstanding question, therefore, is what accounts for these experiential differences? As identified earlier in this review, there are several potential factors which may encourage embodiment. However, the full range of these have not been explicitly investigated. Examples of such factors could relate to prosthesis design (e.g., sensory feedback), contextual factors (e.g., activities undertaken with the prosthesis), or personal characteristics of the user (e.g., presence of a phantom limb). Murray (2004) found both those who experienced their prosthesis as part of them and only as a tool occurring in established prosthesis wearers, those who had persevered with their prosthesis. However, there may be individual differences in how these two broad types of experience of the prosthesis influences rehabilitation. For example, some may need to feel the prosthesis is part of them, whereas others may be happy to continue using the prosthesis simply as a tool. Thus, PE could impact on rehabilitation and possibly be one of the deciding factors in whether the prosthesis is persevered with, at least for some users. Given the complexity of the experience of embodiment, qualitative data on how users perceive and talk about embodiment of their prosthesis is a sensible starting point to gain further insight into this process.

From a literature review of 22 existing qualitative studies on amputees, only two of these specifically focused on embodiment of a prosthesis. This highlights the limited focus previous research has placed on PE and the need for further research to develop understanding in this area. In particular, there is a need to identify which factors can influence PE. Aside from the limited focus on PE in general, these two studies did not directly explore the range of factors influencing embodiment. Murray's (2004) Interpretive Phenomenological Analysis (IPA) study focused on various themes relating to the perceptual experiences of prosthesis users. One of these themes was the prosthesis experienced as part of the user or as a tool. Thus, the study was not specifically identifying the range of factors leading to or disrupting embodiment. However, Murray did propose that exploring PE could highlight the necessary requirements for rehabilitation to achieve PE and also mentioned in his discussion that future research could identify the correlates of PE. Also, his study findings provided specific clues to some of these factors, such as the influence of a phantom limb and its spatial properties in relation to the prosthesis. Consequently, Murray's research has inspired the current study, and PhD in general, along with acting as a stepping stone towards identifying factors associated with PE.

Wijk and Carlsson's (2015) Content Analysis study focused on one specific aspect relevant to embodiment, sensory feedback, along with investigating a variety of perceptual experiences similar to Murray's (2004) study. This study found that sensory feedback from the prosthesis had an important influence on embodiment, particularly highlighted by participants who had previously been involved in experiments with a prototype prosthesis providing sensory feedback. They reported use of the prosthesis provided instant ownership of the limb, whereas many of the participants experienced their own 'standard' prosthesis, with a lack of sensory feedback, only as a tool. As the vast majority of prostheses do not provide sensory feedback, yet some users of these conventional devices still report strong embodiment of their prosthesis, it remains unclear which factors influence successful PE. Also, the evidence in support of embodiment being an inherently positive attribute, or associated with positive benefits, is currently unclear. Embodiment being desirable has been largely assumed by researchers, and potential benefits of embodiment have been speculated on rather than explored empirically, aside from identifying potential consequences of PE, prosthesis users may also shed light on the range of experiences of embodiment and how embodiment changes over time.



In summary, there is a greater need for understanding PE, including how the prostheses are experienced, if PE changes over time, identifying the range of potential individual factors which could influence PE, and possible outcomes of PE. The qualitative study aims to develop general understanding of PE along with specific aspects, proposed to be potentially beneficial for rehabilitation services and/or prosthetics designers on the requirements for achieving PE.

**2.7.3 Survey study on factors associated with embodiment.** The qualitative study was designed to identify the range of potential factors influencing embodiment, the potential outcomes of embodiment, and how embodiment can change over time. It was also designed to identify any individual differences in how users describe their feelings towards their prosthesis which may characterise embodiment or lack of embodiment, and reveal if there are possibly different levels of embodiment. The survey study follows on from the findings of the qualitative study. This was needed to test statistically if there are relationships between specific factors and PE, as suggested by the qualitative findings. In addition, further exploration of this area in a larger sample was required to clarify potential individual differences which emerged from the qualitative study.

Specifically, it was useful to know, based on a measure of embodiment, how many endorse feeling a certain level of PE. This may allow for estimating the prevalence of embodiment or lack of embodiment in a larger sample. It is also unclear which aspects of PE are endorsed more highly. Thus, measuring PE across a range of items would allow for exploring which specific items might best capture embodiment. In addition to this, specific terms provided in relation to PE in the qualitative study were utilised in the survey. This could enable consideration of whether they are associated with PE, and whether they warrant inclusion in future PE measures (e.g., exploring how highly each term is scored). Also, any individual differences in such experiences of a prosthesis could potentially be more identifiable from a larger sample, obtained via questionnaire, than the qualitative study.

The survey allowed for exploring whether there is an association between desire for embodiment and whether PE occurs or not. It was also be beneficial to know the prevalence for desire for embodiment for the sample as a whole to understand its relative importance, as there may be individual differences in whether PE is actually desired. How a person has

experienced their PE changing over time (e.g., a gradual change or temporary change) was measured in the survey, and then each type of change associated with PE. This could help identify whether PE gradually emerges, and whether temporary changes are more associated with either PE or a lack of PE (i.e., which is more stable).

Due to the above outlined reasons, a survey study is proposed to be beneficial to explore these potential relationships quantitatively, and also measure embodiment on a range of items. This will both develop understanding of PE, and ultimately should further knowledge to help inform prosthesis design and rehabilitation services on the requirements for achieving PE. A potential additional benefit for future PE research will consideration of individual items measuring embodiment and whether some are more highly endorsed than others.

**2.7.4 VR experimental studies.** Two broad aspects of prosthetic limbs which may have a role in PE, are the functionality and appearance of the prosthesis. Both of these have been found in research as reasons for users abandoning their prosthesis (Biddiss & Chau, 2007a, 2007b). For functionality, the difficulty in controlling myoelectric prostheses has been widely reported (e.g., Biddiss & Chau, 2007a; Chadwell et al., 2016) and can lead to rejection of the prosthesis (Biddiss & Chau, 2007b). Also, appearance of myoelectric prostheses has been reported by users to be of importance to their experience of their prosthesis (Wijk & Carlsson, 2015), and in terms of “not standing out” and appearing as “normal” as possible (Ritchie, Wiggins, & Sanford, 2011). Satisfaction for each of these may be further highlighted in the qualitative study. As functionality and appearance are general aspects of prosthesis design, compared to more individualistic factors (e.g., length of time the prosthesis has been used), the relative impact of these aspects on PE would be useful to explore. This will enable designers to address the problems with function and appearance, and hence likely improve embodiment of future devices.

Regarding functionality, as detailed earlier, myoelectric prostheses include a fixed delay and variability in response, introducing uncertainty over hand behaviour (Chadwell et al., 2016). Saunders and Vijayakumar (2011) also highlighted the importance of predicted response of the prosthesis based on intended movement (feed-forward model) for functionality. Such feed-forward models have also been identified as being important for the feeling of agency and body ownership (Kalckert & Ehrsson, 2012). This is highlighted by a

version of the RHI, in which a participant moves their hand and sees a rubber hand move. If the command movement (participant's own hand) and response movement (rubber hand) are synchronised this can lead to ownership and agency over the rubber hand (e.g., Kalckert & Ehrsson, 2012). Similar studies have replicated this finding using virtual hands (e.g., Sanchez-Vives, Spanlang, Frisoli, Bergamasco, & Slater, 2010; Yuan & Steed, 2010), and when movement is asynchronous this can disrupt embodiment. Thus, the timing of intended movement with actual movement may be one of the factors influencing whether or not PE occurs for functional prostheses.

Research has shown the RHI, despite being less vivid, is still possible with modality-mismatched feedback, for example, replacing touch with vibration (D'Alonzo & Cipriani, 2012; D'Alonzo et al., 2015). Whilst this utilised the traditional visuo-tactile stimulation RHI (e.g., feeling and seeing paintbrush strokes on hands), it is anticipated an equivalent effect may occur with visuo-motor stimulation, for example, with a prosthetic hand being controlled with muscles flexes. However, it is currently unknown what impact the control method (i.e., controlling movement with muscles flexes compared to natural hand movement) has on embodiment.

As appearance has been raised as important for some prosthesis users, this could also be a factor influencing PE. Potential support for this is a virtual hand ownership study which found that moving a human looking virtual hand produced stronger feelings of ownership than an abstract looking hand (Argelaguet, Hoyet, Trico, & Lécuyer, 2016). The question remains whether a similar effect would be found between ownership of prostheses of varying appearances. For example, it would be useful to explore whether a virtual prosthesis more 'natural' in appearance influences the degree of ownership differently than one which appears more 'robotic'. There may be an interaction between delay and appearance on ownership, and as Ritchie et al. (2011) argues, function and appearance should be considered together.

An IVR study consisting of two parts is proposed to systematically measure the impact of control method, then movement delays and appearance on ownership and agency. The consequent aim being to understand how these factors might influence embodiment of myoelectric prostheses. IVR is particularly useful to explore the research questions as it offers the ability to manipulate the visual world as it appears to participants, specifically to control variable factors (Kilteni, Groten, & Slater, 2012). In the planned studies this can first

include altering the control method of the prosthesis whilst keeping the visual presentation of arm movement constant. Then altering the level of temporal synchrony between participants' motor commands and virtual hand movement, and altering the specific appearance of the virtual prosthesis.

In the first study, before delays or appearance are considered, the control method of a virtual prosthesis will be explored. This will consider the impact of using muscle contraction, instead of natural hand movements, on embodiment. The study will also explore various other aspects of PE and help inform the design or interpretation of the follow-up VR study. For understanding PE, these include exploring the relationship between ownership and agency to see if these aspects of embodiment influence each other (e.g., a greater feeling of agency potentially encouraging a feeling of ownership). Also, exploring the relationship between ownership and physiological responses to a threat applied to the virtual prosthesis. If such a relationship exists it might suggest that with PE, users behave as if the prosthesis is their own arm, when it is threatened. For informing the follow-up VR study, these include identifying the overall level of embodiment achievable with the VR system and control of the prosthetic hand. This is important as a certain level may be needed before delays are introduced. An additional aspect useful to explore, is the accuracy of the virtual prosthesis and whether any specific accuracy issues (e.g., incorrect movement of virtual fingers) have an impact on the measures of embodiment. In the second part of the study, the impact of specific delays (both fixed and variable) of hand movement and appearance of the prosthesis, on PE will be measured.

### Chapter 3: Qualitative study on factors associated with embodiment

Some researchers have proposed that a prosthesis user should incorporate the prosthesis as part of them and this is arguably an aim of prosthetic rehabilitation (De Preester & Tsakiris, 2009; Dhillon & Horch, 2005; Moraal et al., 2013; Murray, 2004; Van Lunteren et al., 1983). More specifically, it has been suggested that PE may be related to a person's decisions regarding wear and use of a prosthesis, thus encouraging embodiment could be beneficial for rehabilitation. PE may have a direct influence on use due to the limb feeling part of the user, and thus encouraging more natural and regular use of it. Incidentally, Makin et al. (2017) note that clinicians and engineers have considered that rejection of a prosthesis can happen due to the limb not feeling as a body part, however, this consideration is currently an untested assumption. In addition, it is also unknown what the other cognitive, behavioural, and affective outcomes of PE might be.

Murray (2004) found that the reported experience of the prosthesis as a tool, or prosthesis as body part, could both occur in established prosthesis wearers, i.e. those who had persevered with their prosthesis. This may suggest no impact of embodiment on long-term prosthesis adoption. However, there may be individual differences in how these two broad types of experience of the prosthesis influences rehabilitation. For example, some users may *need* or *desire* to feel the prosthesis is part of them, whereas others may be happy to continue using the prosthesis simply as a tool. Thus, PE could impact on rehabilitation and possibly be one of the deciding factors in whether the prosthesis is persevered with, at least for some users. In order to help facilitate PE, the factors influencing its occurrence need to be understood.

Given the complexity of the experience of embodiment, qualitative data on how users perceive and talk about embodiment of their prosthesis is a sensible starting point to gain further insight into this process. From a literature review of 22 existing qualitative studies on prosthesis users, only two of these specifically focused on embodiment of a prosthesis. This highlights the limited focus previous research has placed on PE and the need for further research to develop understanding in this area. In particular, there is a need to identify which factors can influence PE. Aside from the limited focus on PE in general, these two studies did not directly explore the range of factors influencing embodiment.

Murray's (2004) Interpretive Phenomenological Analysis (IPA) study focused on themes relating to the perceptual experiences of prosthesis users. One of these themes was the prosthesis being experienced as part of the user or as a tool. Thus, the study was not specifically identifying the range of factors leading to or disrupting embodiment. However, Murray did propose that exploring PE could highlight the necessary requirements for rehabilitation to achieve PE and also mentioned that future research could identify the correlates of PE. Also, his study findings provided specific clues to some of these factors, such as the influence of a phantom limb and its spatial properties in relation to the prosthesis. Consequently, Murray's research has inspired the current study, along with acting as a stepping stone towards identifying factors associated with PE.

Wijk and Carlsson's (2015) Content Analysis study focused on one specific aspect relevant to embodiment, sensory feedback, along with investigating a variety of perceptual experiences similar to Murray's (2004) study. This study found that sensory feedback from the prosthesis had an important influence on embodiment, particularly highlighted by participants who had previously been involved in experiments with a prototype prosthesis providing sensory feedback. They reported use of the prosthesis provided instant ownership of the limb, whereas many of the participants experienced their own 'standard' prosthesis, with a lack of sensory feedback, only as a tool. As the vast majority of prostheses do not provide sensory feedback, yet some users of these conventional devices still report strong embodiment of their prosthesis, it remains unclear which factors influence successful PE.

Whilst several researchers assume embodiment to be a desired experience for prosthesis users (De Preester & Tsakiris, 2009; Moraal et al., 2013), the evidence in support of embodiment being an inherently positive attribute, or associated with positive benefits, is currently unclear. Likewise, the potential benefits of embodiment have been speculated on rather than explored empirically. Benefits could potentially include the amount of prosthesis use, proficiency with the prosthesis, functional improvements (Wijk & Carlsson, 2015) or increased intuitive control of the prosthesis (Makin et al., 2017).

A further benefit of embodiment may relate to improved body image. PE involves incorporating the prosthesis into the user's body image representing a previously experienced 'complete' form (e.g., for amputees), and/or a form considered more acceptable by society (e.g., for those with congenital limb absence). Thus, in either case, an improved body image

might be expected, which in turn may have psychosocial benefits for the user. However, the link between PE and an improved body image has not been directly explored by previous research.

Another potential outcome of PE is a reduced awareness of the prosthesis. Supporting this possibility, integration of the prosthesis with a user's body image was found to have the consequent effect of a reduced awareness of the prosthesis in Saradjian et al.'s (2008) study and Moraal et al.'s (2013) case study. Additionally, if the prosthesis is internalised in an equivalent manner to using a tool (Churcher, 1984), i.e., incorporated into the body schema as an extension of the body, this can result in the loss of focal awareness of the prosthesis (Murray, 2004).

Aside from identifying potential consequences of PE, prosthesis users may also shed light on the range of experiences of embodiment and how embodiment changes over time. For example, it is currently unclear if embodiment develops gradually over time and/or temporarily changes as a result of a specific factor. On the one hand, if embodiment is related to skill or amount of wear, it is reasonable to expect that users will experience a gradual strengthening of embodiment. It is also possible that users may experience fluctuations in embodiment linked to contextual (e.g., social environment) or behavioural factors (e.g., current activities). Of course, a gradual change and temporary change are not mutually exclusive experiences.

In summary, there is a greater need for understanding PE, including how the prostheses are experienced, if PE changes over time, identifying the range of potential individual factors which could influence PE, and possible outcomes of PE. The study aimed to develop overall understanding of PE, along with identifying specific factors associated with PE. Knowledge of such factors is proposed to be potentially beneficial for rehabilitation services and/or prosthetics designers on the requirements for achieving PE, in addition to identifying the potential benefits of encouraging PE.

The qualitative study research questions are:

- 1) What themes emerge when prosthesis users discuss their experiences of embodiment?

- 2) What factors are perceived by prosthesis users to influence PE?
- 3) How do prosthesis users experience changes to PE over time?
- 4) What factors are perceived by prosthesis users to be influenced by PE?

Based on the literature review, specific factors were expected to have relevance for PE, in terms of influences and outcomes. See Table 2 for these factors.

Table 2

*Summary of factors influencing PE and outcomes of PE*

Influences	Outcomes
Phantom limbs	Increased prosthesis proficiency
Amount of prosthesis use	Increased prosthesis use
Sensory feedback	Improved body image
Length of time with prosthesis	Reduced awareness of the prosthesis
Type of prosthesis	Satisfaction with prosthesis
Awareness of prosthesis	
Satisfaction with prosthesis	
Body image	

### 3.1 Method

**3.1.1 Design.** A qualitative approach was considered necessary to further develop understanding of the experiential aspects of PE. The acceptance and use of a prosthesis is a complicated process (Saradjian et al., 2008) which could be influenced by variation among the unique histories and psychological characteristics of the users. Thus, semi-structured interviews are an appropriate method allowing discussion of topics previously identified along with exploring unexpected factors.

Individual interviews were conducted instead of focus groups due to the personal nature of prosthesis use and the potential individual circumstances for each user. Therefore, a one-on-one interview was considered more beneficial for the research aims, to avoid an individual's responses being biased through discussion with other users. Email interviews were conducted for methodological benefits: to increase the opportunity for a larger sample as this allows for geographically distant recruitment. Additionally, continued contact with the participant allows for providing further information or issues to be clarified later on. Email interviews come with the added advantage of not needing transcription. Murray's (2004)



qualitative study of prosthesis users included email and face-to-face interviews, and found email interviewees were more direct or honest in their responses, provided a deeper reflection on experiences, and answers were more focused on the research questions. The additional time to respond was considered a possible reason (Murray, 2004).

**3.1.2 Participants.** As a broad approach was taken to participant recruitment (either limb absence through amputation or being born without a limb, missing either one or both limbs, all levels of upper limb absence, and no pre-determined length of time since amputation/prosthesis-use), through a variety of sources, it was difficult to pre-determine the sample size. Qualitative studies tend to have smaller sample sizes than quantitative studies due to their nature of a detailed analysis, so either have a relatively small target sample or the data collection is terminated earlier due to saturation (no new information being discovered). A review of qualitative studies with amputees was conducted to find an appropriate sample size, which was found to range from 1-42 ( $M = 16$ ). With the greater difficulty in recruitment of upper-limb amputees, studies with such a population were focused on, with three having samples of 8, 11, and 13. The smallest and largest of these used a similar method (Content Analysis) to the current study, so with this in mind and the aims of the research, a sample of 10-15 was sought.

Participants included any upper limb amputees or those with congenital limb absence who are using or previously used a prosthesis. They were over 18 years old, could write in English, and were able to email regularly. See Table 3 for information on participants' limb absence.

Table 3  
*Background details of participants and limb absence*

Gender		Age		Number of countries	Unilateral or bilateral		Amputation cause		Congenital	Level of limb absence	
M	F	M	Range		U	B	T	D		Below elbow	Above elbow
6	4	45	25-73	5	8	2	5	1	4	7	3

*Note.* M = Male; F = Female; U = unilateral; B = bilateral; T = trauma; D = disease.

Table 4

*Background details of prosthesis use*

Years of prosthesis use		Years between limb absence and first prosthesis use		Prosthesis replacing amputee dominant hand	Type of prosthesis*		
<i>M</i>	Range	<i>M</i>	Range		C	B	M
21	1-67	2	1-6	4	2	5	2

*Note.* \*Nine out of ten participants. C = cosmetic; B = body-powered; M= myoelectric.

See Appendix A for full details of participants represented in Table 3 and 4.

**3.1.3 Recruitment sources.** Sources included amputee charities/organisations which have websites or newsletters, forums relevant for amputees/prosthesis users, and social media groups. As NHS ethical approval was not arranged these did not include rehabilitation centres. See Table 5 for a summary of the number of sources contacted and outcomes. Also, see Appendix B for a complete list of sources.

Table 5

*Summary of sources contacted to advertise the qualitative study and outcomes*

Sources ( <i>N</i> = 84)	<i>n</i>
Replied	33
Supported	30
Social Media	18
Forum	9
Website News	10
Newsletter	3
Magazine	2

*Note.* Supported = said they would be happy to support the research or I noticed they posted the advert.

**3.1.4 Materials.** A generic introductory email to send to sources was created. In addition, sources were sent 2 study adverts to share online with their readers, with each containing a link to an online study poster. See Appendix C for these documents. A background information form was created to collect specific information from participants e.g., demographics information, details of limb absence and details of prosthesis use. An

interview schedule was developed as an outline guide of questions (see Appendix D, for interview schedule and background information form), which was based on a range of initial factors expected to be relevant for PE identified from the literature review (Chapter 2). The interview schedule included questions about how the participant felt towards their prosthesis (e.g., their relationship towards it, how they felt towards their prosthesis compared to their anatomically-intact limb, (if relevant), how their feelings changed over time, what factors they considered had influenced their feelings (i.e., influences on the presence or absence of PE), and what outcomes they felt were influenced by their feelings (i.e., outcomes based on the presence or absence of PE). A Coding Manual was created including these initial factors and altered when new factors emerged or changes to initial factors became relevant (i.e., the document content was fluid across the data gathering and analysis period). Initial development of the coding manual involved creating sections which individual factors were grouped within (e.g., a section of feelings towards the prosthesis, a section on influences, a section on outcomes). Individual factors were created from factors identified as relevant influences or outcomes in the literature. These included a factor name and a definition. This was used to identify the presence of factors and PE in interview transcripts (see Appendix E for the coding manual). An Excel spreadsheet was used during the analysis to code participant's interviews (see Appendix F, factor names in red are newly emerged factors). Also, see Appendix G for the ethical approval letter. See Appendix H for additional research documents (Participant Information Sheet [PIS], Consent Form, Debrief sheet).

**3.1.5 Procedure.** Sources were emailed requesting a representative to post the advertisement (e.g., on their website or through a newsletter) or for permission to self-post it (e.g., on a forum). A standardised email was adjusted for the source to request specific places for the advertisement. Once a potential participant made direct contact via email and it was checked they had read the information sheet and if they had any questions, the consent form was emailed to them for electronic completion. Upon receipt of the completed form an individual participant number was emailed. A rough interview completion time was initially discussed, but expressing that this is flexible. Questions were emailed initially one at a time (occasional multiple questions were sent where appropriate), and the guide was loosely followed to ensure areas of interest were covered, along with any additional points raised by the interviewee. Once completed, participants were asked if they wished to add any further information and were debriefed. Questions and responses from emails were formatted in a

Word document as an interview transcript including their participant number. See Appendix I for an example interview transcript.

**3.1.6 Analysis procedure.** A Directed Content Analysis (DCA, Hsieh & Shannon, 2005) was conducted on the interview transcripts to identify factors influencing PE, time-course of embodiment, and potential consequences. DCA takes both a deductive and inductive approach, with initial codes developed from findings of previous literature and new codes emerging from the interviews or analysis. DCA is a suitable method as: 1) previous research has identified some potentially relevant factors which the analysis can build upon, and 2) it is compatible with quantitative analysis, which could be useful for designing later quantitative experiments. Each completed interview transcript was coded to the spreadsheet. If a participant raised a relevant factor that was not previously included in the Coding Manual, it was added to the manual. The meaning unit was a specific extract in the transcript which could be applied to a code relevant to the research aims. Codes were grouped within broad themes and one such theme *Factors influencing feelings towards prosthesis* was split into sub-themes. See Table 6 for an example of the coding process.

Table 6  
*Example of coding process to theme*

Meaning unit	Code	Sub-theme	Theme
The most important thing I have learned about wearing a prosthetic, is that it's a long process, and requires a lot of patience and practice. I believe that it requires a lot of time practicing using it, and the more you wear it the better.	Amount of use of prosthesis	How the prosthesis is used and how long for	Factors influencing feelings towards prosthesis
As I have previously compared my prosthetic to shoes, I guess it feels comfortable and reliable like an 'old pair of boots'.	Satisfaction with reliability	Satisfaction with prosthesis	Factors influencing feelings towards prosthesis
I think the feeling I have of my prosthesis feeling part of my body definitely influences how I feel about my body.	Body image changed overall		Overall outcomes of feelings towards prosthesis

An inter-rater reliability analysis was conducted on two interviews (20% of the sample). This involved another member of the research team using the completed coding manual to code interviews on a separate coding scheme spreadsheet. Comparisons between the two coding were analysed for percentage of agreement. To assess a suitable percentile agreement for each factor, a minimum suggested coefficient amount of 0.80 has been recommended (Neuendorf, 2002). Out of 64 factors, 16 factors (25%) were below 80%, with 48 (75%) having 100% agreement. Any discrepancies were discussed to check how respective coding was being conducted and finalise the coding scheme. This resulted in 100% agreement on all factors.

### **3.2 Analysis/Discussion**

Factors of interest were grouped into 5 broad themes based on the initial research questions. During analysis 2 new themes emerged, as highlighted in red. These were added as several participants mentioned temporary influences of their embodiment and also outcomes of embodiment which were temporary in nature. These are listed below and a description of each will be provided in each theme section.

- 1) Feelings towards prosthesis
- 2) Factors influencing feelings towards prosthesis
- 3) Factors influencing temporary feelings towards prosthesis
- 4) Overall outcomes of feelings towards prosthesis
- 5) Temporary outcomes of feelings towards prosthesis

The analysis produced a total of 63 factors across the 5 broad themes. This included 17 factors at the start of the interview process, and 46 additional factors which emerged during interviews and ongoing analysis. This section highlights the most interesting and significant of the findings in each grouping, with emphasis on the unexpected new factors, findings and inter-relationships (i.e., beyond existing literature) which were revealed during the interviews.

**3.2.1 Feelings towards a prosthesis.** The theme ‘Feelings towards a prosthesis’ captures the different ways that users feel about and perceive their prosthesis, and their relationship to it. Factors coded under this theme include descriptions of how a prosthesis feels in relation to

a user's body or self, whether such feelings have changed over time or temporarily, and whether there is a desire or need to feel that the prosthesis is part of them. Such feelings were either described on their own during the interview, or in relation to a specific factor (either as an influence or outcome). See Figure 2 for the number of people who experienced different types of overall embodiment.

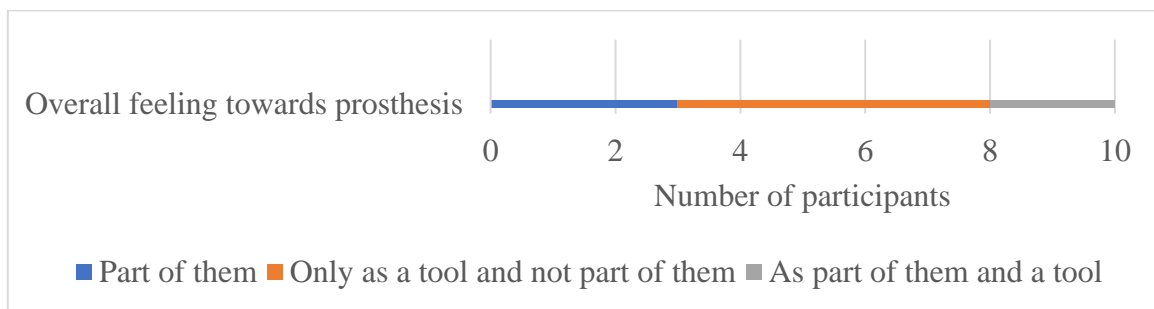


Figure 2. Frequencies of types of embodiment.

Unlike specific codes, an overall feeling towards a person's prosthesis was identified from a range of criteria either based on one or multiple codes for an individual. Each aspect will now be detailed. *Part of them* includes when the person describes their prosthesis as a part of them, part of their body or incorporated into them, they feel ownership over it, feeling part of their self. Three out of ten participants were identified as feeling that their prosthesis was part of them:

*In general, my prostheses feels like a natural part of my body...as far as I'm concerned, they are "part" of me. This isn't to say I think of them as actual limbs - I just mean that they're integrated strongly into my sense of self. (P3)*

P3 notes how their prostheses feel part of them and a natural body part. They also highlight that despite not thinking about them as real limbs, they are integrated into their sense of self.

Interestingly, some participants reported experiencing their prosthesis as both '*part of them and a tool*'. This code includes when the person described their prosthesis with any *Part of them* descriptors along with describing their prosthesis as feeling as a tool. 2 out of 10 participants reported considering their prosthesis as both part of them and a tool, as highlighted below:

*My prosthetics are both part of me and tools: I suppose hands are part of the human body, but are also tools, a way to do/make/accomplish things. I feel them more as part of me though, probably because I always used them since I was young, and so I just grew up with them. (P2)*

Here, P2 shows how they consider their prostheses as both part of them and a tool. This may have come from them having congenital limb-loss, as they were born missing both hands and are here speculating about hands naturally being part of the human body, but also serving as a tool to help facilitate actions. However interestingly, despite not having hands from birth, they feel their prostheses more as a part of them and suggest this due to growing up with them since a young age.

Consistent with the work of Murray (2004), some participants reported the prosthesis as ‘*Only as a tool and not part of them*’. This code includes describing their prosthesis as just a tool, not any of the ‘part of them’ descriptors. 5 out of 10 participants reported not feeling their prosthesis as part of them, instead with the prosthesis acting as a tool or aid in their life, sometimes for a variety of reasons (e.g., functional, cosmetic, social norms):

*I don't feel that my prosthesis is part of me but wearing it is who I am. It is similar to wearing glasses or hearing aids. Close companions, essential, but their usefulness is entirely up to me to get the most out of them. (P5)*

P5 reveals that despite their prosthesis not feeling part of them, it is related to their social identity. They also consider the utilitarian nature of their prosthesis by comparison with glasses or a hearing aid. See Figure 3 for the number of people who experience specific feelings towards their prosthesis.

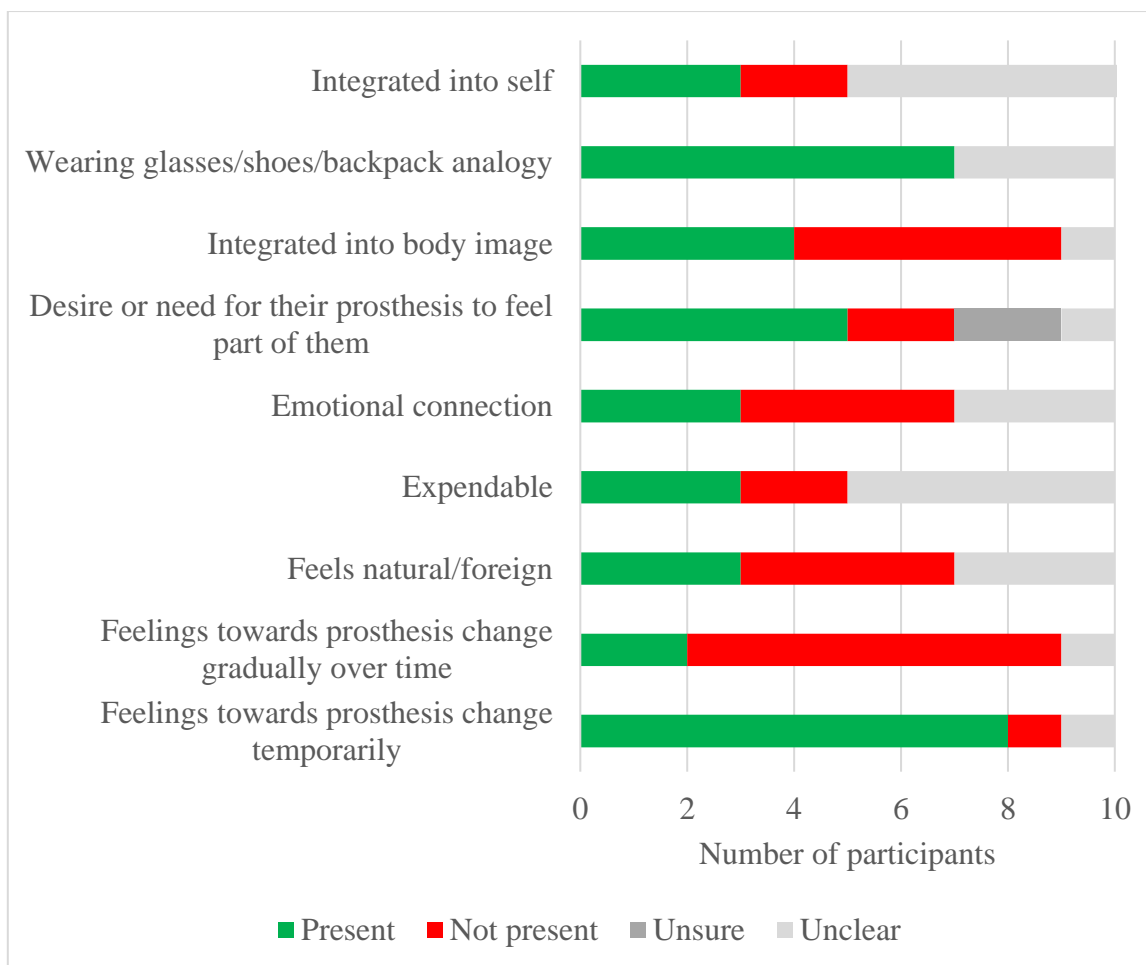


Figure 3. Frequencies for feelings towards prosthesis.

The factor ‘integrated into body image’ covers cases where the prosthesis is described as feeling part of their physical body or as a body part. This was explained in a variety of ways. Whilst some simply reported their prosthesis feeling like part of their body, others provided an alternative representation:

*When it’s in for repair, I literally feel like someone has cut off my left hand, ha ha!!!*  
(P6)

P6 notes a strong sensation of their left hand having been cut off when the prosthesis is away being repaired. This suggests their prosthesis is represented within their body image. However, some did not experience this, for example:

*I identify my arm as a needed tool and not so much as a part of my body* (P7)



Here, P7 directly refers to their prosthesis not feeling part of their body, instead identifying it as a tool. Integration into body image characterises one aspect of the prosthesis feeling part of a user (or not, as displayed above), with another aspect of being ‘part of them’ relating to their sense of self.

Some participants reported their prosthesis feeling part of them, but described in terms of them as a person, or their sense of self, rather than as part of their physical body. This was mentioned in part of an earlier extract:

*I just mean that they're integrated strongly into my sense of self. (P3)*

*My arm really is an extension of me and after 40 years I don't know anything else. (P1)*

P1 mentions their arm being experienced as an extension of themselves. Such experiences highlight how some users can feel a strong connection to their prosthesis beyond representing it as a body part. This connection may relate to having a ‘relationship’ with their prosthesis that might not occur with a tool that is not attempting to replace a body part.

Interestingly, participants differed in terms of whether they desired or needed to feel PE, or the relative importance of this compared to other factors. This has been a central research question beyond exploring specific outcomes of PE and was equally relevant to explore in those who experience PE, and those who do not. An example of the former:

*I think that I do have a desire for it, but it's not the most important thing. The embodiment is almost like a luxury that I would give up if I needed to.... But because the embodiment relates to my functionality, I'd prefer having the embodiment feelings if possible. (P3)*

P3 notes that they do have a desire for PE, but there are other more important factors. Despite this, they highlight that due to specific outcomes of PE (in their case improved functionality) they still desire to experience their prosthesis as part of them. This provides a clue for the potential importance of PE for some users, and potential outcomes will be discussed in detail in the outcomes section. However, some others did not desire to have PE:

*Gradually I was able to appreciate the physical advantages of a prosthesis but I cannot remember ever wanting it to be more than that...*

*My prosthesis is a wonderful aid to everyday life. I do not want it to be part of me. Rather to support my everyday life unnoticed by me. (P5)*

As P5 notes, appreciation of how their prosthesis supports them in their life, does not necessarily mean that a person wants their prosthesis to feel part of them. This suggests an individual difference in what they desire from, and thus what motivates them to use, a prosthesis.

Through exploring how participants felt towards their prosthesis, this revealed a greater range of experiences which were not previously considered components of PE, but here suggest they might be. Some participants felt an emotional connection with their prosthesis and this could manifest as a behavioural response. Whilst, this can't be revealed with such a qualitative study, it could be important to consider in future studies as a proxy for PE (e.g., in designing questionnaires to measure embodiment):

*Yes, I think that emotional reaction was related to feeling like the prostheses are part of me. It was almost like a possessive reaction, where I had the sense of "that's mine and I don't want you touching it." It may be a similar reaction if a stranger just walked up to you and lifted up your arm! In that case, you'd probably feel out of control of your body because someone else was doing something with it without your consent or control. (P3)*

Here, P3, who experiences embodiment, had an emotional reaction in response to a stranger touching her prostheses. This reaction further emphasises the feeling of body ownership over the prosthesis. Whilst some reported having a similar relationship with their prosthesis, others had no emotional connection. In this sense they considered their prosthesis to be expendable, meaning they would not miss their prosthesis beyond the practical benefits it provides them, if they had to be without it:

*I appreciate having my prosthesis but it is expendable and if it had to be replaced, there would be no emotional consequence. (P5)*

These feelings might characterise the prosthesis as an object worn on the body but with no specific psychological investment. Such a proposal was highlighted by some participants comparing their prosthesis to wearing shoes, glasses or other bodily-worn object. This comparison was explained in multiple ways. Some used the analogy of wearing an external object as shown below with shoes:

*I would not imagine another person feeling that shoes would be considered a part of them, but would not think twice about stating that they are everyday tools in their life. The fact that a prosthesis is replacing a limb that was once there is likely the only reason this question would be asked. I believe it to be a valid question, only that most people would consider that a loss of limb leaves a person devoid of wholeness. Therefore, must have "feelings" toward a prosthetic device they use. (P7)*

Interestingly, P7 through comparing their prosthesis to shoes as useful "tools", highlights the individual expectation of whether the prosthesis should feel part of them. Their elaboration that most people would expect to have feelings towards their prosthesis, because of them feeling incomplete, suggests the influence of what an individual, desires or expects from their prosthesis. Other participants literally described their prosthesis as feeling like a worn object rather than using this as an analogy:

*I would describe it as "foreign" ...not PART of my body...with the straps to hold it on... the lack of "feeling" it just feels like something I have on. Like a backpack or a side shoulder bag. (P10)*

Here, P10 describes how their prosthesis feels just like an object they are wearing and that this is due to the straps securing the prosthesis and the lack of sensory feedback. In addition, as highlighted here, experiencing the prosthesis as not part of them and just as something they are wearing can also be associated with feeling it as a foreign object. However, other participants who experienced PE, instead described their prosthesis as feeling natural and not like a foreign device:

*In general, my prostheses feel like a natural part of my body. (P1)*

Similar to previously mentioned factors (emotional connection, expendable, feelings like glasses/shoes/backpack analogy), this factor may have implications for future studies of PE if the “naturalness” of a prosthesis is an aspect of PE. Such feelings of naturalness were mostly reported in terms of their current feelings. However, in one example this feeling was experienced as changing over time:

*At first it felt foreign, and now it is my "normal" ....it has begun to feel more natural to me. (P11)*

A prosthesis can potentially develop from being experienced, initially as a foreign object, to one that feels more natural. The change in naturalness might also potentially mirror PE changing gradually over time, however, many participants did not have a conscious recollection of this occurring. For those who did experience a gradual shift towards PE, this was reported in relation to other factors, such as P6’s experience:

*I'd say that over time my feelings have increased. As I have previously compared my prosthetic to shoes, I guess it feels comfortable and reliable like an 'old pair of boots'. The more I do with it, over time the more it feels part of me. (P6)*

P6 notes how their sense of embodiment had gradually increased and they also noted the intertwined nature of time and use, suggesting both may be an influence of PE. In addition, P6 interestingly used the analogy of their prosthesis feeling like an old pair of boots, which is comfortable and they can rely on. In this sense, the comparison relates to comfort and reliability, rather than feeling the prosthesis as an externally-worn object. This discrepancy suggests a potential complication with the idiosyncratic use of this analogy, in addition to the potential usefulness of this factor as a proxy for PE (i.e., feeling like glasses suggesting the lack of PE) in future studies. The variability in how the prosthesis can be experienced, or comparisons made to other objects, suggests the potential involvement of individual differences in PE.

Whilst, participants on the whole did not experience the gradual development of PE, they more commonly reported a temporary shift in PE. This means they believed their feelings temporarily changed as a result of a specific event, either to become more or less a part of them than how they normally feel:

*My feelings do change at times regarding my prosthetic. If I am having a bad day with the way it fits, or trouble getting the hook or elbow to work I just want to take it off and forget about it for a while. (P11)*

P11 who normally feels their prosthesis as part of them and is proud of their accomplishments, highlights how this feeling can temporarily reduce, resulting in them wanting to remove it and not think about it. By contrast, a participant who usually doesn't feel their prosthesis as part of them had a temporary shift in the direction of feeling PE:

*A time when it feels more a part of me? Yes. New Years Eve when a group sing Auld Lang Syne and hold my hand quite naturally...I think the dancing anecdote was important to me from the point of view of public acceptance and probably reveals a deep psychological aspect (P5)*

In contrast to P11's experience, P5 does not usually experience PE but could perceive feeling their prosthesis temporarily more as part of them, due to the positive reaction he perceived from others towards his prosthesis. This was the only example of this trend. In addition, those with PE tended to report more shifts in their experience than those without. Such differences may suggest another individual difference, that of likelihood of fluctuation of PE. Specific factors influencing temporary changes will be discussed further in the following section.

**3.2.2 Factors influencing temporary feelings towards prosthesis.** This theme explores specific factors which influence temporary feelings towards the prosthesis. As in, feelings towards a person's prosthesis change temporarily (compared to overall) as a result of something specific. See Figure 4 for the number of people who experience factors temporarily altering their PE.

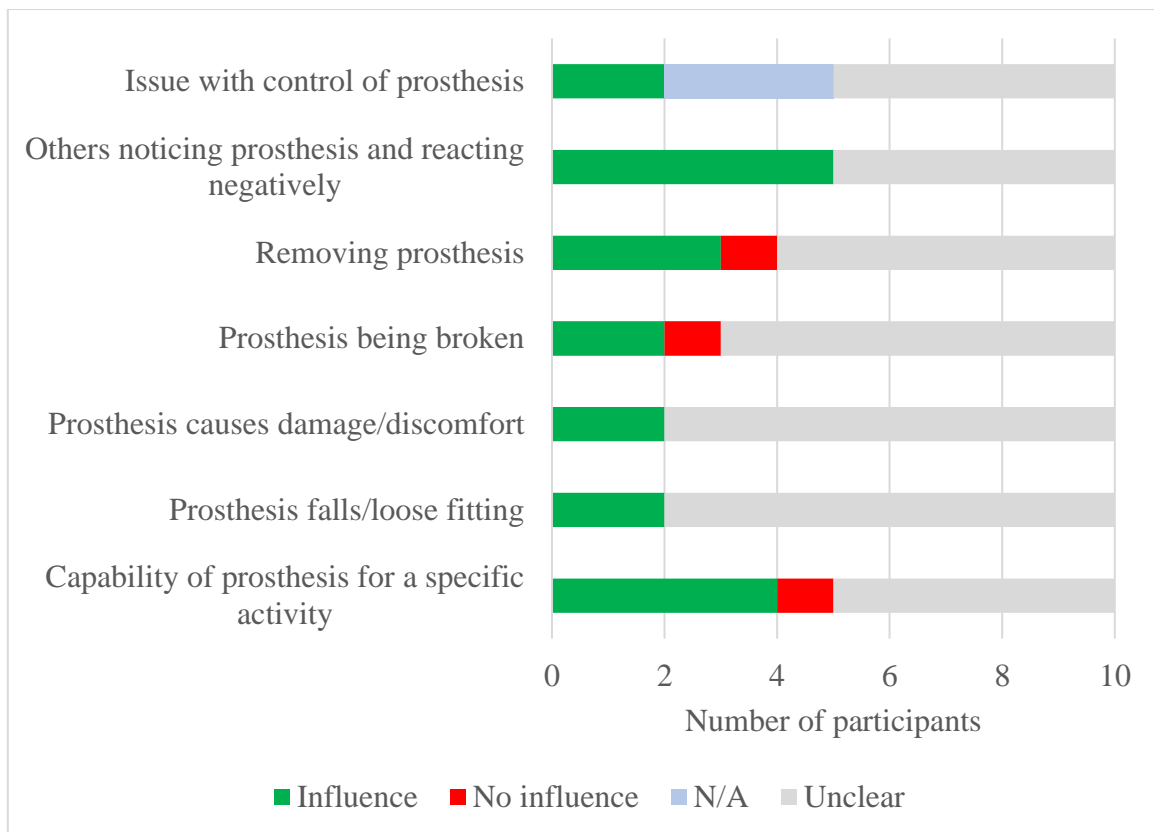


Figure 4. Frequencies of temporary influences.

Participants reported temporary shifts in PE as being due to such factors as when the prosthesis is removed, broken, causes damage to the user or is uncomfortable, or has a loose fitting. Loose fitting could increase the chance of the prosthesis malfunctioning, e.g., the electrodes functioning correctly for a myoelectric prosthesis.

Having an issue with controlling the prosthesis can temporarily influence PE, as explained here:

*When my socket has not fit well, or the placement of the electrodes is not right, it makes using my prosthetic a very frustrating experience. I have been at the grocery store, and could not open or close my hook or stop the wrist from spinning. I actually have just turned the arm off a couple times when I have had moments like this. At these times it has made me feel out of control, and it can be embarrassing. At those moments the prosthetic arm feels more like a tool that is broken and useless. It can be exhausting to try to get the arm to function when the socket is loose, and there isn't good contact with the electrode sites. (P11)*

P11 mentions how if electrodes are not placed correctly, they can have an issue with maintaining control, making them feel in that moment their prosthesis is just a tool and is broken. This factor also relates to a further temporary influence, that of the capability of the prosthesis for a specific task.

Another aspect relating to a final temporary influence which emerged from interviews, involved perception of others reacting to their prosthesis. This is the influence from a specific type of attention drawn towards the prosthesis at a particular moment. When there was a lack of attention this also had an influence, as described by P1 encouraging PE for him even further:

*When people don't notice my prosthetic arm and hand that's when it really is part of me - I have fooled them!...*

*When others don't notice my prosthesis, it feels even more a part of me. When others notice my prosthesis, it brings my attention to it and it feels less a part of me. (P1)*

Interestingly, P1 mentions how different types of attention influences his PE differently, such as the opposite effect, where external attention towards their prosthesis reduces the sense of PE. The impact of such attention appears to relate to the negative reaction of others towards prosthesis users, as highlighted by P11:

*Or when I am in public and negative reactions from people can make me feel bad. If I get frustrated with the fit or function, or negative reactions from people can influence how I feel. (P11)*

P6 further elaborates on how another person's behaviour in response to their prosthesis results in P6 doubting themselves and experiencing reduced PE:

*Also, as I've previously said, if someone notices my arm, and their attitude and behaviour towards me changes, then it can make me doubt my feelings towards my arm, and I feel I am almost questioning myself? (P6)*

As pointed out by P6 and others, the naturally experienced level of PE can easily fluctuate depending on the reactions from others. This suggests an important social component of PE, which will be discussed further in the following theme on overall influences of PE.

**3.2.3 Factors influencing feelings towards prosthesis.** Factors influencing feelings towards prosthesis are those for which a specific factor is believed to influence (or not influence) the person’s overall feelings towards their prosthesis (i.e., whether it feels part of them or not). Thus, an influence can either encourage or discourage PE.

**3.2.3.1 Sub-theme 1: Aspects of the person.** This sub-theme focuses on specific aspects of the person, separate to their prosthesis, which they perceive to be an influence over whether they experienced PE or not. The sub-theme includes whether the person had congenital limb absence or was an amputee, if they experienced phantom limb sensations, and where these were spatially in relation to their prosthesis, if they had a positive mindset towards being successful with their prosthesis, and their sensitivity to the amount of negative attention they receive from others. See Figure 5 for numbers of people who relate aspects of themselves as an influence of their PE.

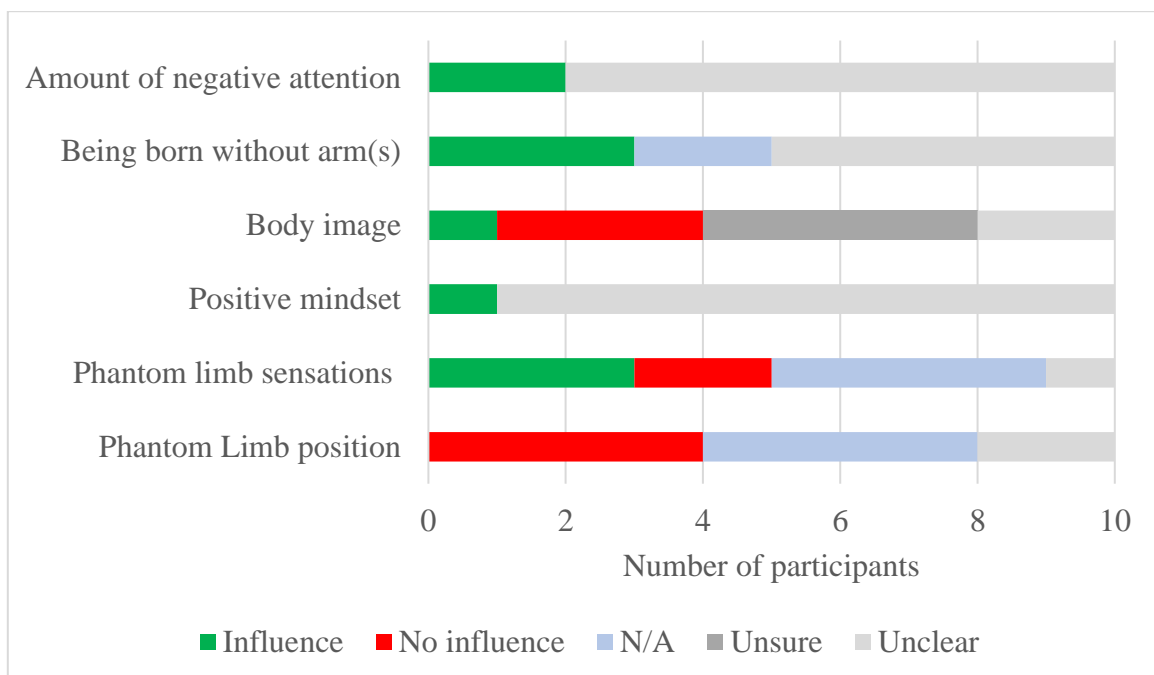


Figure 5. Frequencies of personal aspects (sub-theme 1).



The amount of negative attention participants perceived from others overall had influenced whether they experience PE:

*I previously had a split hook from quite an early age, so I had a very negative attitude towards my arm, which was due mainly to the way people viewed me, such as name calling at school etc. Once I was given a mechanical hand, people viewed me differently, and I became more accepting of it, and over time any negative feelings disappeared. This was at an early age, I was probably about 8 or 9 years old. (P6)*

P6, who experiences PE, mentions how their feelings were associated with their overall perception of negative attention. This is particularly interesting as they were able to compare different times in their life where attention from others differed, along with their change in feelings. Thus, the relationship between negative attention and PE could be intertwined with their PE changing over time. This shift in PE could possibly be experienced across different broad periods of time (e.g., when using a specific device at different times in the user's life as in the example above), or temporarily experienced (e.g., at the point in which the negative attention is received, represented embodiment both relates to feelings changing over time and, as will be discussed in a later section, how a specific experience of attention can temporarily influence a change in PE.

The relative impact of negative attention may relate to two other factors, the type of limb absence and how positively someone feels towards their body image, both of which will be discussed next. Relevant for whether someone desires their prosthesis to feel part of them or not, one of the factors which emerged as an influence of PE was whether someone was born without their arm(s). Interestingly, out of 4 congenital amputees, 3 of them reported that missing their arm from birth was an influence but participants differed in whether this encouraged or discouraged PE:

*I was born with one arm only and grew up accepting that mistake. My first prosthesis at the age of 5 or 6 was worn with reluctance because I was happy as I was...*

*I do not feel, or want, it to be a part of me. I was born with one arm and do not miss what I have never had. But I am so grateful that wearing it helps to make so many things possible. I suppose part of it is accepting life as it is and I am fortunate that*

*this is my state of mind. I have not had to work at it - it is the way I am. If I felt the need to strive for an alternative state of mind, I would not be content. (P5)*

Here, P5 highlights how being born missing one arm contributed towards them not experiencing PE, due to not having a previous arm which they now miss. This resulted in their contentment and lack of desire for their prosthesis to feel part of them. Such feelings characterise a motivational aspect of PE where users may vary in what they want from their prosthesis. In this specific case, what was desired from the prosthesis was driven by the user's prosthesis not replacing a previously lost arm. However, the same situation resulted in the opposite for other users:

*I guess with not having a left arm from birth, and not knowing any different, I guess I treat it as 'another' body part, in that it functions as an arm would do normally, granted that its only to a certain extent...as a congenital prosthetics user, I don't have anything to compare my 'left arm' to, except my various artificial arms. (P6)*

Interestingly, as explained by P6, not having an arm from birth can actually help to embody the prosthesis, due to not having a previous anatomical limb to compare it to. This potentially suggests that, for amputees, attempting to replace a previously experienced arm might make PE harder to achieve. Thus, the potential challenge in gaining PE may be partly influenced by the limitations of the prosthesis in closely matching their previously experienced natural arm. Overall, the type of limb absence may also relate to the impact from body image on PE. P5 who earlier related their lack of PE to not having their arm from birth, also discussed the influence of their body image (before using their prosthesis) on their feelings towards their prosthesis:

*I was quite happy in early childhood, so why should I want something extra to my body? Body image when not wearing a prosthesis was not an issue with me. I remember a lady on the beach pointing out my limb absence to a friend. I would be 5 or 6 and this was the first time this (a conscious memory) had happened. After that I wanted to look like everyone else but it was the image that was important, not having an addition to my body. (P5)*

P5's detailing of their wholeness discouraging PE, due to not wanting an addition to their body, reveals an important potential influence of body image. In addition, whilst P5 mentions the impact of another person's behaviour on their body image (but not PE), the relevance of body image for other prosthesis users could be more profound. Such users' level of PE could be both impacted by body image and negative attention from others, highlighting a social component to PE. Unfortunately, the relevance of body image was overall either unclear or reported to have no influence by amputees for a variety of reasons (e.g., not being concerned with or thinking about their body image at a certain age, having a desire for PE to improve body image yet still not experiencing PE).

However, even for those who did endorse the relevance of this factor, there were contradictions in how body image influenced PE. Instead of a positive body image discouraging PE, a clue from another participant points towards a negative body image making it harder to accept wearing their prosthesis:

*The negative feelings did not influence or encourage my feelings about my prosthetic being part of me. If anything, the negative feelings influenced fear of wearing a prosthetic arm. (P11)*

Despite P11 having PE, they pointed out that if their negative body image had any influence it was in terms of fearing the use of a prosthesis, rather than encouraging their PE. P11 is an amputee so it is unclear if the discrepancy between their account and P5 (who has congenital limb absence) is due to type of limb absence or their body image. This evidence, combined with previously mentioned findings, suggests that type of limb absence has a complex role in experience of PE. There is not a simple relationship between the cause of limb absence and embodiment. Rather, having limb absence from birth can either encourage or discourage PE, potentially depending on an individual's baseline body image (e.g., sense of wholeness).

One factor likely relevant to a personal desire for PE, and potentially relevant for how someone responds to negative feedback, is how positive they feel towards becoming a successful prosthesis user. Thus, having a positive mindset was reported as an influence on PE. Only one participant reported this:

*I believe having a positive mindset that I was going to be successful, and consistency with wearing and using "my arm" each day had some impact on how I feel as well. At first, it took a lot of courage to go out in public with my arm. I learned quickly to avoid looking at people (because of all the stares), and to concentrate on the task at hand (like at the grocery store when I use my arm to help bag produce). I decided early on that I was going to not worry about what people thought when they look at me with or without my arm. I decided early on that I was going to have a positive attitude, and not let anything stop me from living a full life as an amputee. So I guess having a positive mindset and courage, have also influenced my feelings about "my arm". (P11)*

P11 details how having a positive attitude towards their prosthesis helped encourage them having PE. They also highlight how this relates to the impact of negative attention from others, and how much the prosthesis is used. The latter factor belongs to a separate theme so will be discussed later.

The relevance of body image for the individual could also have a social component, as some participants reported that the amount of negative attention, they perceived from others had influenced whether they experience PE:

*I previously had a split hook from quite an early age, so I had a very negative attitude towards my arm, which was due mainly to the way people viewed me, such as name calling at school etc. Once I was given a mechanical hand, people viewed me differently, and I became more accepting of it, and over time any negative feelings disappeared. This was at an early age; I was probably about 8 or 9 years old. (P6)*

P6, who experiences PE, mentions how their feelings were associated with their overall perception of negative attention. This is particularly interesting as they were able to compare different times in their life where attention differed, along with their change in feelings. Thus, the relationship between negative attention and PE could be intertwined with PE changing over time. This shift in PE could possibly be experienced across different broad periods of time (e.g., when using a specific device at different times in the user's life as in the example above), or temporarily experienced (e.g., at the point in which the negative attention is

received further highlighting that whilst factors can influence PE overall, there is also a temporal component of PE.

Other aspects which influenced PE were found to be the presence of phantom limb sensations, with the specific influence on PE depending on whether pain was present (discouraged PE), and the position of the phantom limb (congruent with the prosthesis).

**3.2.3.2 Sub-theme 2: Aspects of the prosthesis.** This theme involves the potential influence from various aspects of the prosthesis, including broad differences such as the type of prosthesis, how the prosthesis is controlled (for functional/active prostheses), repeated changes to the prosthesis, whether the visual appearance of the prosthesis has been personally customised, the amount of sensory feedback provided by the prosthesis, and the specific benefits which the prosthesis affords/provides the user. See Figure 6 for numbers of participants who consider specific aspects of their prosthesis to influence PE.

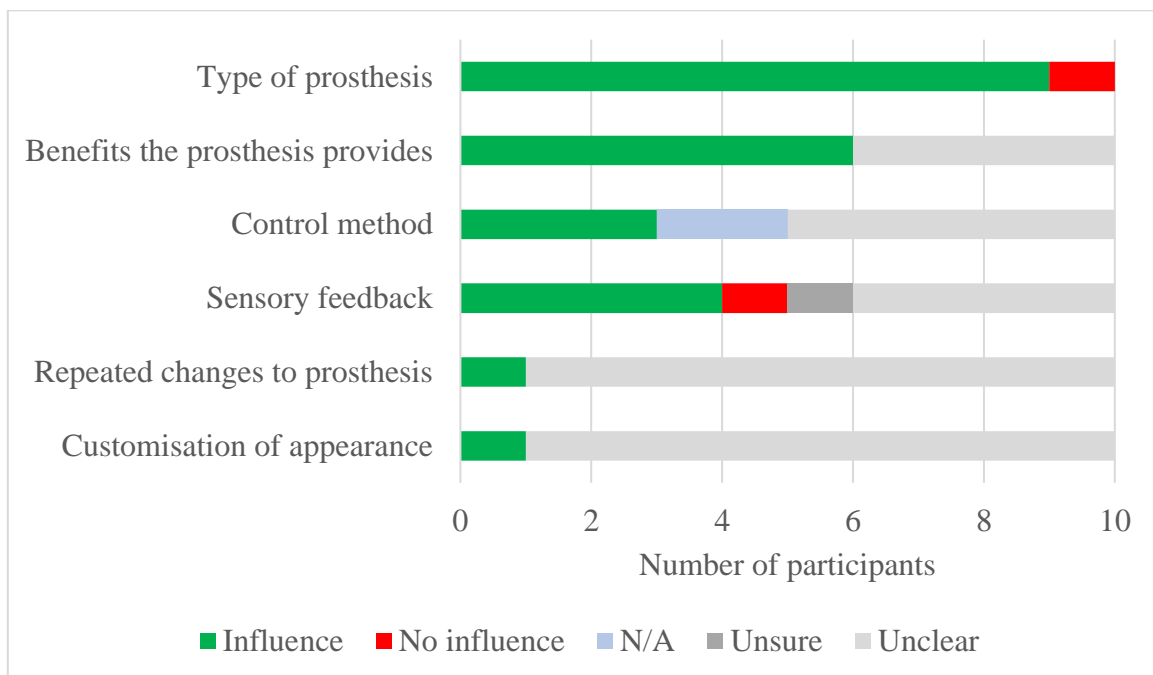


Figure 6. Frequencies of prosthetic aspects (sub-theme 2).

The broad type (e.g., cosmetic, body-powered or myoelectric) or specific type of prosthesis (e.g., different materials used in their prosthesis) was reported to be an influence on their experience of PE. P2 owned multiple types so they could directly compare their relative feelings towards the different types of prostheses they owned. For the interview, they

focused on their body-powered prostheses feeling part of them, which they then compared with other types:

*For myoelectric it is a similar story, but for cosmetic, honestly I have never thought of the issue. I probably feel them more like accessories/tools, as they are only useful to appearance, even if I managed to learn to do many things with them. (P2)*

P2 shows how type of prosthesis may have an influence over PE, in the sense of their non-functional prosthesis feeling less a part of them and only acting as a tool, due to their main role of supporting appearance. Interestingly, here they consider the focus on the cosmetic function of the prosthesis resulting in them feeling more like an accessory/tool. This differs, to P1 who uses a cosmetic prosthesis but feels this as part of them. However, in contrast this participant considers the benefits which their prosthesis brings them (including benefits beyond cosmetic functions) to encourage their PE, again highlighting the individual differences aspect of PE.

How a prosthetic hand is controlled in functional prostheses was considered important for some participants in terms of encouraging or discouraging PE. Despite having the added function of hand control with such prostheses, this might not contribute towards PE. In some cases, this was reported to actually hinder the prosthesis feeling part of the user due to the unnatural control method:

*This is where I had/have the most difficulty. it was a mental issue for me. When I wore either prosthesis, mentally I didn't have an arm. In other words. I had to THINK about it when I never did before. I had to move my shoulders to open or close the body powered or I had to flex my Tricep or Bicep for the myoelectric...*

*YES the extra movements made it also feel like it was not part of me. I would have to move my biceps or triceps to open the hand...*

*the extra movements DEFINITELY had an influence. since I am an Above Elbow amputee. having to "set" the elbow on the myoelectric had a big influence. having to "think" about how I used the arm. (P10)*

P10 did not experience PE and partly attributed this to the control method, of both their body-powered and myoelectric prostheses. They also related this to other relevant factors from the analysis, the overall type of prosthesis as discussed, and how much they had to think when controlling their prosthesis. The importance of this will be later discussed in a separate theme.

In contrast to P10, one participant felt that their control method of their prosthesis actually encouraged PE:

*Just the fact of being able to think about opening my hand (hook) to grab something, makes it feel natural, not mechanical, has influenced my feelings. I think having a manual prosthetic would be much lighter in weight, but I am not sure it would feel like a natural movement when doing a task. I know that my manual elbow can frustrate me at times, just trying to get it in the correct position at times. I had TMR surgery a year ago...I love the advanced technology, and I feel that I am fortunate to have access to it....*

*When I am doing tasks, I don't feel like I have to think hard about making it function. It feels like natural movement most of the time....Being able to control movements with my thought process is amazing...is a huge contributor to feeling "a part of me" because it is uniquely me. My thoughts, my nerves, my muscles, and my prosthesis communicating, and working naturally together...*

*the electronic elbow makes it feel even more like it's part of me...*

*I do think that the electronic elbow does feel more a part of me due to the fact that I have to think about bending my arm to make it function. (P11)*

P11 had undergone *Targeted Muscle Reinnervation* (TMR), a surgical procedure allowing for intuitive control of a myoelectric prosthesis. They highlight how the natural feeling of controlling the prosthesis encourages it to feel part of them. This suggests a potential difference to normal control of myoelectric prostheses using EMG control via muscle flexes, as noted by P10 as a reason for their prosthesis not feeling part of them.

Other participants reported the varying influence of sensory feedback from their prosthesis (e.g., feedback on stump or other body part, specific sounds from the prosthesis interacting with objects) on their PE. Interestingly, despite all participants not having true sensory feedback, which is only available to a certain extent even in advanced prosthetics, the limited feedback influenced PE in different ways:

*I think, for me to feel it is part of me, it would need to have feeling. It would need be touch sensitive. Without that— a very human trait, it is really just a tool...*

*I believe that without the true feeling of touch and sensory input, a prosthesis is truly a tool above all else...*

*I do believe that lack of sensory input affects my ability to feel it is a part of me and therefore to consider it a tool. It is like anything else that has no direct input to your body — sacrificial (P7)*

P7 clearly identifies their lack of sensory feedback as a reason for why they do not experience PE. Another participant elaborated on the implications of the lack of sensory feedback:

*I would describe it as "foreign" ..not PART of my body..With the straps to hold it on... the lack of "feeling" it just feels like something I have on..like a backpack or a side shoulder bag...*

*YES.. the amount of feedback was an issue. could not FEEL when I was holding something..."did I pick up the cup? am I holding the cup too tight? too loose??"*  
(P10)

P10 highlights how having no sensory feedback makes them feel like their prosthesis is just an external object worn on their body, and how this disrupts their ability to interact with objects accurately. However, another participant felt their limited sensory feedback encouraged their PE:

*I alluded to this already, but I think the sensory feedback from the prostheses helps them feel like part of me. Of course the feedback is different than what you get from a*



*natural limb, but I'm still able to interpret it. Beyond the visual feedback from watching the hands move, I listen to the sound of the motors and feel vibrations through the socket. This is not something I usually pay explicit attention to, but I do rely on that feedback quite a bit. (P3)*

P3 reveals how they make use of their limited sensory feedback and how this actually encourages their feeling of PE. These discrepancies between participants could either reflect actual differences between their prostheses, based on type or subtle differences within each type (e.g., fitting), or individual psychological differences (e.g., individual conscious awareness of sensory information).

Other aspects of the prosthesis which were found to have relevance for PE included various alterations made to the prosthesis, such as repeated changes made to the prosthesis and customisation of the visual appearance of the prosthesis.

**3.2.3.3 Sub-theme 3: Satisfaction with the prosthesis.** This theme includes various aspects relating to the prosthesis but specifically in terms of the subjective satisfaction the participant has. Such specific aspects were found to be relevant for some users regarding their experience of PE. These aspects include satisfaction with functionality, appearance, fitting, comfort or weight, reliability, response speed, and noise of the prosthesis. Satisfaction with each of these aspects does not mean the participant is 'fully' satisfied with their prosthesis, but rather their subjective level of satisfaction and whether this interacts with their experience of PE. Each will now be briefly covered with discussion at the end. See Figure 7 for the number of participants who vary on their satisfaction with aspects of their prosthesis.

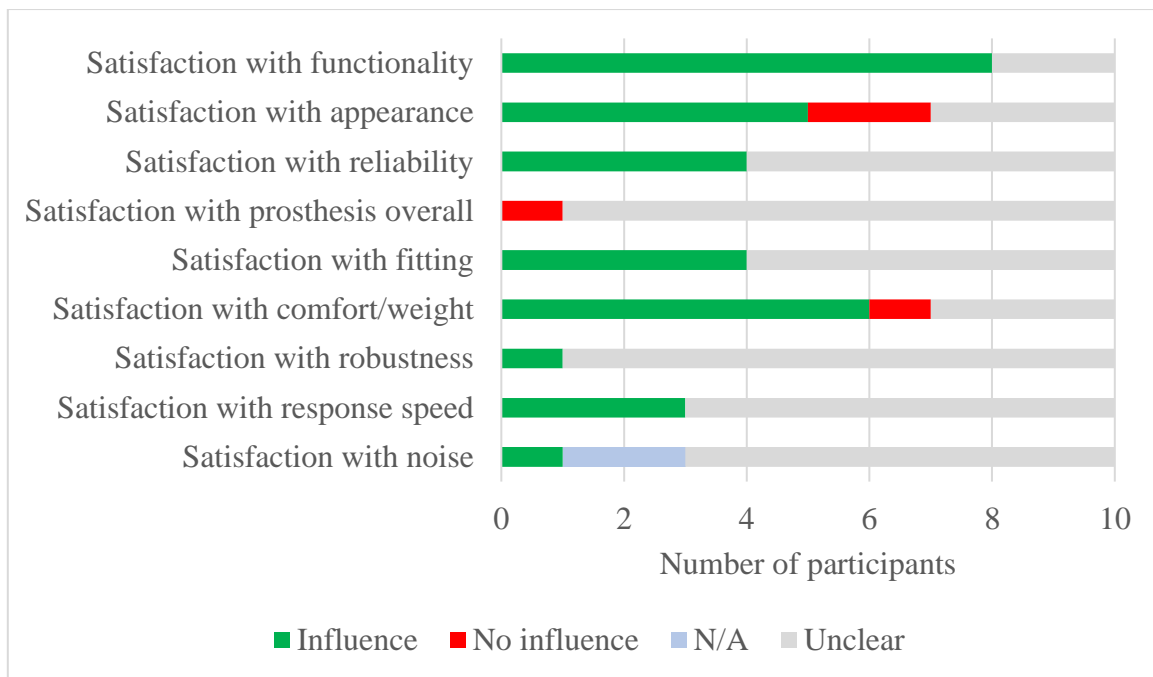


Figure 7. Frequencies of satisfaction with prosthesis (sub-theme 3).

Subjective satisfaction with the functionality of the prosthesis was considered important by many participants, and this either encouraged or diminished PE, based on the level of satisfaction:

*I think my mechanical hand feels the most part of me, in that I use it the most, it is the most adaptable, and I suppose I have the most confidence with it to perform the best in everything I do. (P6)*

*As far as the functionality of my myoelectric arm (it's actually a hybrid myoelectric prosthetic), the advanced technology has definitely influenced the feeling of being a part of me. (P11)*

*Yes, it is a much-needed device for my everyday activities. Without it, I am really unable to do so many of the things that I am required to do to fulfil my job duties. So, I am really satisfied with my hook as a useful tool, however, it could be made better. It has limited capabilities. I'd say it is 30% as useful as a hand. But infinitely more sacrificial, so that is one aspect that makes it easier to do certain things that may be far too dangerous with a real hand, and, therefore, helps boost the level of satisfaction. (P7)*

Interestingly P7 points out how the sacrificial nature of the prosthesis, compared to an anatomical hand, enables a greater amount of activities with the prosthesis, consequently increasing their level of satisfaction. This highlights the subjective nature of satisfaction and how individual differences may play a role in how a user considers their functionality. However, not all participants shared this level of satisfaction of their prosthesis, as mentioned by P10:

*Yes my satisfaction with it's functionality.. or lack of.. influenced my feelings and I chose not to use it. (P10)*

As revealed by participants, satisfaction with functionality and its impact upon PE was described in different ways depending on the person and what they consider their prosthesis useful for. The relative importance of functionality was also compared with satisfaction with appearance, which was also considered important for some user's sense of PE:

*satisfaction in that it nearly resembles a real arm (P1)*

*I had envisioned a very boring plain metal prosthetic at first, and was not too thrilled about it. The appearance of my prosthetic has clearly influenced my feelings...*

*The similar shape of my prosthetic arm compared with my missing limb influences this as well. When I first saw how much the shape looked like my missing arm, I felt better about body image, and more open to wearing a prosthetic arm. I recently found a picture of me taken a year prior to losing my arm, and was amazed at how much it looks like my missing arm (the shape). (P11)*

The relative importance of appearance compared with functionality was also raised by some participants:

*I do think satisfaction is part of it. I have cosmetic covers for the prostheses that look pretty realistic so that can help me (and others) visually perceive them as "real*

*arms. "...The satisfaction with functionality is probably more important than the cosmetic satisfaction though. (P3)*

Here participants revealed that satisfaction with appearance could involve numerous aspects including, the similarity in the prosthesis resembling an anatomical arm overall, appearance exceeding prior expectations. In one example the participant considered the relative importance of appearance being lower than satisfaction with functionality. This suggests potential individual differences over which aspects of a prosthesis are of most importance to them, potentially having a greater influence on their level of PE.

Another aspect of satisfaction involves two related factors, that of how well the prosthesis is fitted, and how satisfied the user is with the reliability of the prosthesis. This may also relate to control method and type of prosthesis, highlighting the intertwined nature of factors:

*I do think the proper placement of the electrode sites and having a well fit socket helps tremendously. I have had several fittings and adjustments, especially in the beginning. The "correct" positioning is a process, and takes time to get it right. The shape of my residual limb has changed over the last couple of years, and the adjustments to the sites and socket are necessary. It definitely adds to making my prosthetic feeling a part of me when I am able to connect my thoughts (my phantom limb), and make the mechanical parts function. (P11)*

How well the prosthesis is fitted to the user appears to be an overall influence on PE, but is related here by P11 to issues with control of the prosthesis and having a loose fitting. If there is a poor fit of the socket or prosthetic interface then a poor bond between the user and prosthesis would be expected, and might naturally lead to poor PE. A poor fitting has also been highlighted as an influence on the functioning of myoelectric prostheses (Head, 2014). These factors can also temporarily influence PE as mentioned previously. Satisfaction with fitting could also be related to how comfortable the prosthesis feels, which emerged as an additional factor:

*As I have previously compared my prosthetic to shoes, I guess it feels comfortable and reliable like an 'old pair of boots'. (P6)*

It became apparent that satisfaction with reliability was described by participants in two different ways. Here P6 considered their prosthesis 'reliable' because they can depend on it, like an old pair of boots that are also comfortable. Whereas participants also referred to the technical reliability of their prosthesis functioning. For example, P11 who discussed the reliability of her myoelectric prosthesis electrodes working correctly and relating this to how well her prosthesis was fitted.

Overall, the various aspects of this theme reveal the multifaceted nature of satisfaction with the prosthesis in terms of how they can each influence PE depending on each individual's circumstances and potential individual differences in the relative importance of each aspect. Ultimately, any of these factors could contribute directly towards PE, and/or indirectly via how much or whether a prosthesis is used which was also shown as a potential influence of PE. The latter of which forms part of the following theme.

**3.2.3.4 Sub-theme 4: *How the prosthesis is used and how long for.*** This theme includes various ways in which the prosthesis is used, such as the age when the person first starting using their prosthesis, how much they used their prosthesis initially (i.e., when first received after amputation or when a congenital limb-loss user begins using their prosthesis), overall amount of use, and also the overall length of time with their prosthesis. See figure 8 for the number of participants whose amount of use and length of time with their prosthesis, was considered an influence on their PE.

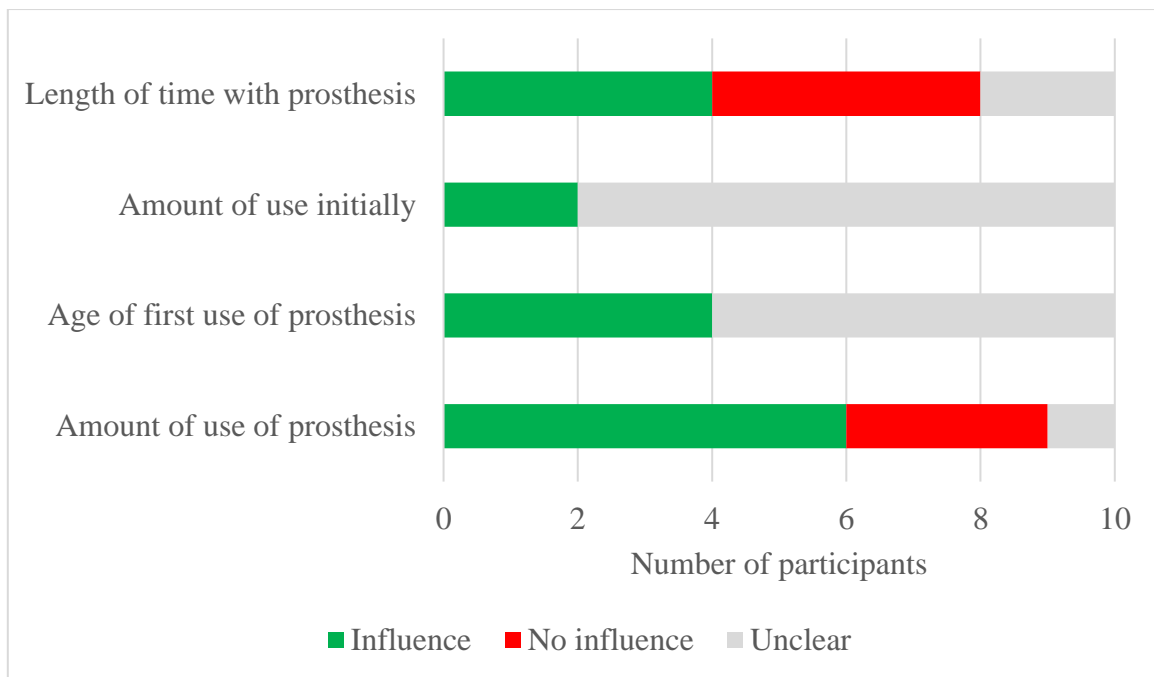


Figure 8. Frequencies of use and time (sub-theme 4).

There was an equal split between participants over whether they felt the length of time they had their prosthesis for had influenced their PE or not. Some felt having their prosthesis for a long time has played a role in their PE:

*It must have something to do with the fact that I had my prosthetic arm so long - I have had it for longer than the right arm/hand that I was born with. (P1)*

Whereas, others clearly noted they felt length of time had no influence:

*No, I don't feel that the length of time I had it, or tried using it had any influence. (P10)*

This clearly suggests an individual difference in whether how long someone has used a prosthesis plays a role in encouraging PE; for some, it seems they may gradually adapt to their prosthesis, with PE developing gradually as detailed earlier, hence having a prosthesis for a longer length of time encourages PE. However, perhaps for other users who do not experience PE, no amount of time would help their prosthesis feel part of them. This suggests that for these individuals, other factors may play a more important role. Interestingly, some participants who did experience PE reported it was more dependent upon when they started

using their prosthesis than how long they had spent with their prosthesis, specifically in terms of using from a young age encouraging PE. In addition to the age of first use, how much a prosthesis is used overall was identified as an important factor influencing whether they experienced PE. Whilst this is related to length of time with prosthesis, more participants overall endorsed amount (intensity) of use of the prosthesis as a factor. This is clearly detailed by P11:

*Yes, over time, and the more I used my prosthesis, it has become to feel more natural to me...*

*The more I used it, the better I felt about my prosthesis. After a few months I was using without even thinking about it...*

*and consistency with wearing and using "my arm" each day had some impact on how I feel as well...*

*I stuck to a schedule of gradually wearing my prosthesis for longer periods over a couple months. The more I wore it and used it, the more it felt like part of me. I think that many amputees, (the non-prosthetic users), haven't allowed enough time learning how to use a prosthetic before giving up. I think it takes time wearing and using a prosthetic before it feels part of you...*

*The most important thing I have learned about wearing a prosthetic, is that it's a long process, and requires a lot of patience and practice. I believe that it requires a lot of time practicing using it, and the more you wear it the better. (P11)*

P11 highlights at various points in her interview about the role of how much she used her prosthesis played in her developing PE. However, not everyone had this experience. Others felt it had no or minimum role in this:

*No, I don't feel that the length of time I had it, or tried using it had any influence...*

*the amount of time I had it... and how much I used it.. had minimal influence. (P10)*

P10 did not have PE and stated amount of use had no influence, suggesting that they considered they had used their prosthesis enough and felt no matter how much they used their prosthesis it would not become part of them. However, it should be noted that amount of use was not quantified, so no direct comparison was made between participants, despite them having their prosthesis for variable lengths of time. Irrespective of this limitation, the discrepancy in reports from participants highlights how for some, amount of use may encourage PE, whereas for others it may potentially not do. A further participant verbalised this idea:

*Yes the lack of functionality is the main reason I do not use my prosthetic and yes I do not feel that if I did use it more that it would feel part of me due to my phantom limb sensation being such a strong feeling. (P8)*

Aside from mentioning amount of use, P8 also highlights how other potential factors may have more importance in determining the presence (or absence in this case) of PE – one being their phantom limb sensations, and the other being their satisfaction with the functionality of their prosthesis.

**3.2.3.5 Sub-theme 5: Level of conscious awareness of the prosthesis and naturalness/ability in task completion.** This theme centres on the participant's level of conscious awareness of their prosthesis, in terms of how much they are aware of their prosthesis overall, or whilst engaging in tasks. It also relates to the need for planning tasks in advance, i.e., whether a task can be completed naturally without too much prior thought, or if this needs to be planned in advance. The theme also includes how proficient they feel in using their prosthesis and how this transmits to natural and skilful use of their prosthesis. See Figure 9 for the prevalence of participants whose conscious awareness, level of skill with their prosthesis and naturalness of task completion impacted on their PE.



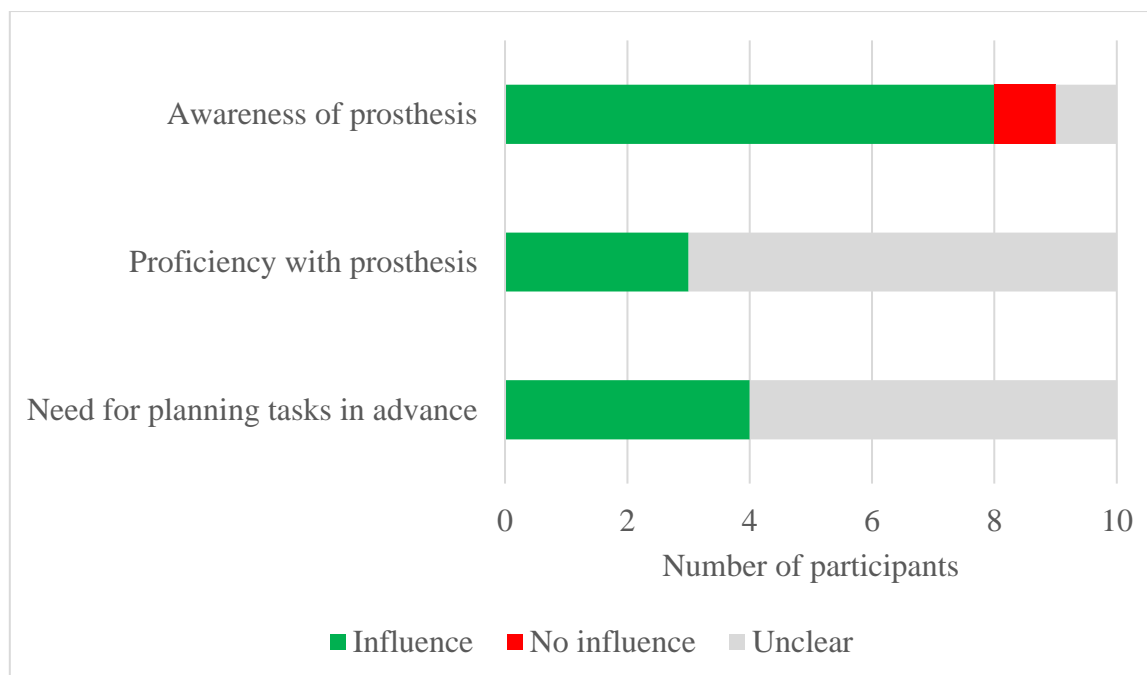


Figure 9. Frequencies of level of awareness of prosthesis naturalness (sub-theme 5).

How much a participant felt consciously aware of their prosthesis was reported by the majority of participants as being relevant for their PE or lack of PE:

*I don't have to specifically focus on the prostheses unless I'm doing a difficult task that requires a lot of concentration (like picking up a really delicate object, for example). Even then, I am paying more attention to the requirements of the task than to the prostheses themselves. When picking up a delicate object, I would need to close the fingers really slowly so that I can monitor the grip force and not accidentally crush the object. However, I know exactly how to contract my muscles to make the prosthesis close slowly, so I'm thinking more about how my body feels (i.e.- the muscles in my residual limb) rather than the prosthesis itself. (P3)*

Here, P3 who has PE, notes how they don't have to place a specific focus on their prosthesis and how this relates to carrying out specific tasks. However, some participants had the opposite experience of this where heightened awareness influenced their lack of PE:

*I have to concentrate a lot on each task with the prosthetic. Firstly, as I do not have an elbow and my residual arm is fairly long, I have an external elbow joint on my prosthetic. Therefore before I even start a task I must find the correct angle for my*

*prosthetic by manually changing the elbow joint. The elbow joint is also limited to an up/down action and can not do a left/ right action, therefore I may need to move my body to get the prosthetic at a workable angle. I then have to rotate the wrist plate to get the hook into the right position. I can then start the task, in which I need to concentrate on operating the split hook, timing, and maintain the right position for the prosthetic to be useable. ....having to concentrate and plan actions means they are not natural. This therefore means my prosthetic does not feel part of me. (P8)*

*YES ABSOLUTELY!!!! I was so used to not having to think about holding a cup.. or how to open a door that it became a mental thing more than a physical one. (P10)*

P8 and P10 did not have PE and reported how their heightened awareness of their prosthesis played a role in this, along with mentioning another factor – the need for planning tasks in advance. Another related factor is how skilful (i.e., proficiency) someone is in using their prosthesis. Three participants, who all have PE, mentioned that feeling proficient in using their prosthesis influenced their feelings. P3 clearly states how her proficiency with her prostheses plays a role:

*There are very few things that I cannot do with the prostheses. I think that this high success rate gives me confidence that I have control over the prostheses and know how to interact with them appropriately...so basically I feel proficient at using them. I think it would be hard to feel connected to something that you don't feel proficient at using. (P3)*

Interestingly, when P3 was discussing her limited conscious awareness of the prosthesis when completing tasks, one part directly referred to the influence of proficiency:

*However, I know exactly how to contract my muscles to make the prosthesis close slowly, so I'm thinking more about how my body feels (i.e.- the muscles in my residual limb) rather than the prosthesis itself. (P3)*

This shows how this factor is intertwined with amount of conscious awareness of the prosthesis. The connection between these factors is also reflected in P11's experiences:

*Yes, the more natural it has become to do a task with my prosthesis has definitely influenced the feeling of my prosthesis being part of me. The ability to use my prosthesis without having to think about it, took some time and training for my brain and residual arm (muscles, shoulders), to connect or synchronize. As using my prosthetic became more of a normal or routine part of the day for me, the better I felt about it. Not having to consciously think about each movement has made it easier, and contributed to the feeling of "my arm" being part of me...*

*I definitely feel that the combination of time spent wearing it, and my ability to make it function without having to think contribute to my prosthesis feeling part of me.*

(P11)

In the latter comment, P11 elaborates on the interaction between amount of use, proficiency with prosthesis, and awareness of prosthesis all contributing towards her prosthesis feeling part of her. This suggests a number of specific factors could play an important role in encouraging PE, at least for some users.

Exploring the outcomes of PE was one of the research questions, but what emerged from interviews was that in addition to overall outcomes, there were also temporary ones. In addition, it was found that the previously assumed positive outcomes of PE were accompanied with a variety of negative outcomes. Positive outcomes were largely characterised by overall outcomes, whereas negative outcomes tended to be those of a temporary nature. Both will now be briefly covered in the following two themes.

**3.2.4 Outcomes of feelings towards prosthesis.** Overall outcomes are something specific happening as a result of the person's feelings towards their prosthesis, where the outcome is general in nature (compared to a temporary outcome). This means the specific outcome of a factor is considered as having been caused by the presence or absence of PE. See Figure 10 for number of people who experienced different outcomes of PE.

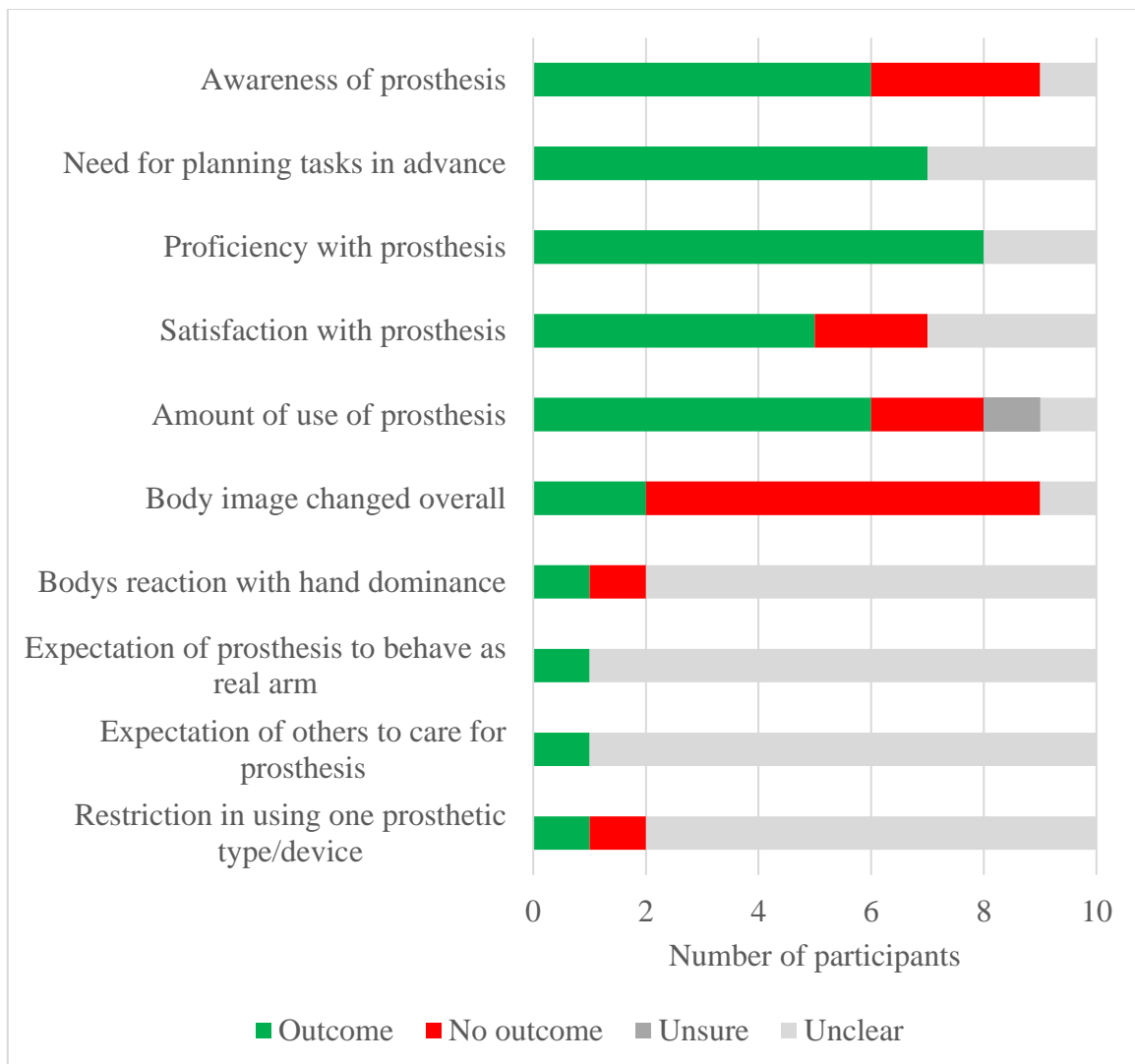


Figure 10. Frequencies of overall outcomes of PE.

Some outcomes focus on how PE can influence a participant’s conscious awareness of their prosthesis (lower awareness with PE), whether tasks need to be planned in advance (less need with PE), and how proficient they feel in using their prosthesis:

*When my prosthesis feels more a part of me I am sure that it helps me do my job better and feel happier in my home/family environment. (P1)*

*As I feel it is part of me when I wear it, I use it to the maximum of my abilities. I was chiselling the mortar off some bricks the other night, and had the bolster set at an awkward angle, but I knew I would be able to complete the task ‘in hand’! I also wouldn’t try holding a brew in my myoelectric, as I know it has a tendency to open when you don’t expect it. (P6)*

*Yes, my feeling of my prosthetic being part of me definitely influences my confidence level and my ability to perform activities with it...My prosthesis feeling part of me definitely influences both my ability to use it, and my awareness of it. When I am having a very productive day and managing to get it to function well, my awareness of it lessens. (P11)*

P1, P6, and P11 highlight how they feel having PE heightens their skill level in using their prosthesis. There were further outcomes of PE mirroring specific influences, which included being more satisfied with the prosthesis and using the prosthesis more:

*I don't think I would use my prosthetic much at all, if I didn't feel that it was part of me. (P11)*

*My feeling that it is not part of me was a VERY big reason why I don't use it...*

*YES..makes me not use it. It feeling not a part of me has been the biggest reason I no longer wear it. (P10)*

P11 and P10's opposing statements reveal how PE can influence amount of use. This suggests that P11 who has PE considers this important for their continued use of their prosthesis, whereas P10 who lacks PE considers this as an important reason for their non-use of the prosthesis. This supports one of the key questions surrounding benefits of PE – whether someone will use their prosthesis more if they have embodied it?

In addition, PE had an influence on body image, with those experiencing PE reporting that their body image was improved as a result:

*I think the feeling I have of my prosthesis feeling part of my body definitely influences how I feel about my body. (P6)*

*I often feel "empowered" when wearing my prosthetic, and most of the time it feels just like part of me, and these feelings influence that confidence about my body image...*

*Yes, overall, my prosthetic feeling part of me, definitely encourages a positive feeling about my body image. (P11)*

Whilst some participants felt PE encouraged a more positive feeling towards their body, the majority reported that their PE or lack of PE did not influence any changes to their body image. This included all the participants with no PE. This might suggest that PE influences body image changes for select individuals. It is also possible that changes only occur for those with PE (i.e., PE leading to improved body image, but not lack of PE leading to a more negative body image). This, however cannot be determined by this study.

Additional outcomes which emerged from interviews included PE influencing the person's reaction in terms of hand dominance. Additionally, PE leading to an expectation of the prosthesis to behave as a real arm, expectation of others to care for the prosthesis, and restriction in using one prosthetic type or specific device. Interestingly, these latter outcomes potentially reflect negative aspects of PE which will now be discussed further with temporary outcomes.

**3.2.5 Temporary outcomes of feelings towards prosthesis.** Temporary outcomes are something specific happening as a result of the person's feelings towards their prosthesis, where the outcome is temporary in nature (compared to an overall outcome). This means the specific outcome of a factor is considered as having been caused by the presence or absence of PE. See Figure 11 for number of people who related specific temporary outcomes to their PE.

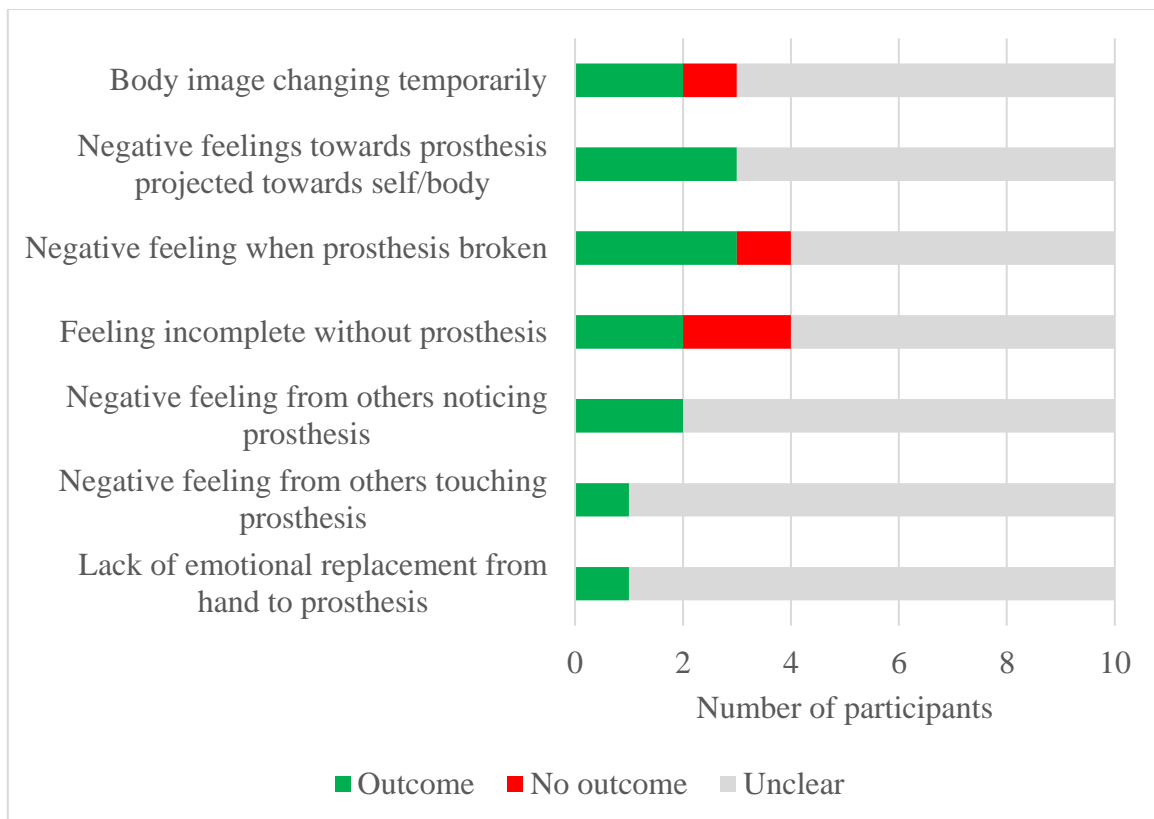


Figure 11. Frequencies of temporary outcomes of PE.

Following the discussion of overall body image changes, body image alterations which are temporary in nature were reported to be negative in nature (i.e., body image becoming less positive):

*I do sometimes have a negative feeling towards my arm, as I have told you previously, such as when I first meet someone and I try to be discreet and almost hide my arm, as I know it can influence peoples first opinion of me. (P6)*

The impact on body image because of the prosthesis feeling part of the user appears related to the broader influence of the prosthesis being processed as a body part, hence negative feelings get projected towards the person or their body:

*That being said, I'm not always emotionally comfortable wearing them. Sometimes I view them negatively, or wish I didn't have to use them. And since they feel like part of me, those negative feelings get directed towards myself. If I'm frustrated with them, its more similar to feeling frustrated with my body than it is to feeling frustrated with a*

*machine. It's a bit hard to explain! For example, I would feel differently about my computer running slowly (as an external machine) than I would feel about my prostheses running slowly (as part of my body). (P3)*

Similarly, for the same reasoning, when the prosthesis is broken this causes a negative affect for someone who has embodied the prosthesis:

*When my prosthetic hand is dirty or the arm locking mechanism is broken, I can have negative feelings towards the prosthesis and I want it fixed very quickly - that day if possible!...*

*When the locking mechanism that locks my hand to my arm breaks I feel helpless and depressed. At that stage I really feel disabled and lacking a functioning arm and hand. (P1)*

The negative feeling when the prosthesis is broken is possibly related to the feeling that part of the person is no longer functioning, and thus they feel incomplete. Such a feeling was highlighted by some participants:

*My prosthetic definitely makes me feel positively about my body, and when I'm not wearing it I really feel I am missing something. (P6)*

The feeling of incompleteness may be subtly different than the negative affect caused by feelings being projected towards the body, when the prosthesis is broken. Such feelings of incompleteness suggest a more overall negative outcome, with the person feeling they are missing part of their body when they have to be separated from their prosthesis for whatever reason. Another temporary outcome of PE relates to the social component of PE, previously touched upon, as in this example:

*if someone notices my arm, and their attitude and behaviour towards me changes, then it can make me doubt my feelings towards my arm, and I feel I am almost questioning myself? (P6)*



P6 who has PE highlights how receiving negative attention can result in a negative feeling, in this case characterised by P6 questioning himself. The suggestion that this relates to their PE implies that such a feeling from a negative reaction might not occur, or occur to a lesser extent if the prosthesis did not feel part of the user. If so, this suggests a further potential negative, albeit temporary, outcome of embodying the prosthesis. It should be noted here that there is a high frequency of 'Unclear' for each factor due to the interview design. This is because temporary outcomes emerged from interviews naturally, rather than existing as pre-mediated categories to discuss (i.e., participants were not asked directly if they experienced such outcomes). Future studies could improve on this through direct enquiry of such factors to identify a more precise assessment.

### **3.3 General discussion**

In summary, prior to this study there was a greater need for overall understanding of PE for arm prosthetics. This included identifying how prostheses are experienced, exploring the temporal aspects of PE, identifying the range of potential individual factors which could influence PE, and further possible outcomes of PE, than previously anticipated. Knowledge of such factors was considered to be potentially beneficial for rehabilitation services and/or prosthetics designers on the requirements for achieving PE, in addition to potential benefits for users of encouraging PE.

The approach taken using a Directed Content Analysis, was to springboard off from factors considered relevant for PE identified in the literature, then identify additional relevant factors which emerged from the interview process and analysis. In this sense, the DCA was successful as it identified a much larger range of factors potentially relevant for PE overall adding new knowledge on PE. This is characterised by the original 17 factors developing into a total of 63 factors, representing 46 additional factors which were not previously anticipated. Specifically, for the Feelings theme, when looking at overall experiences of PE a greater variability in experiences were found.

For feelings towards the prosthesis, some broad differences were found. Half of the sample reported experiencing PE overall, however, others reported their prosthesis feeling like a tool (and not part of them). The broad distinction between the prosthesis feeling part of a user or not supports previous qualitative studies with prosthesis users (e.g., MacLachlan,

2004; Murray, 2004; Wijk & Carlsson, 2015). Despite this, whilst some participants described their prosthesis as part of them, it is not necessarily just part of them or a solely a tool, and perhaps on one level can be considered, while embodied, also as a tool based on what it can provide. This was in fact highlighted by two participants, suggesting a potential third type of embodiment experience. Whilst PE was discussed in broad categories, it appears to be on a continuum and to also contain variable aspects, for example, some described their prosthesis as being part of their body or see it is a body part (i.e., integrated into their body image), whereas others described it as connected to their sense of self, and some mentioned both of these aspects.

In addition, a variety of other ways in which the prosthesis was experienced emerged from interviews (e.g., whether someone has an emotional experience with their prosthesis). Some of these appeared to relate to each other also, so that a prosthesis feeling ‘foreign’ was also described as an external bodily-worn object and felt expendable. Thus, such descriptions may form different but connected aspects of PE which could act as a proxy for PE or be incorporated into future measurements of PE. The association between these feelings and PE was suggested by this study, so a direct association between the factors would need to be explored first before considering their usefulness or direct relationship to PE.

One key unexpected finding which emerged was the temporal nature of PE, in that this was reported to change more temporarily (i.e., fluctuations relative to how the prosthesis ‘usually’ feels), compared to the expected gradual change over time. Such fluctuations were attributed to specific factors but this varied across individuals, suggesting individual differences in how much PE fluctuates and what causes such fluctuation for the person. The limited evidence for PE gradually developing over time was an unexpected finding, in contrast to analogous research suggesting that the body schema of a blind person’s cane gradually develops over time and use (Serino et al., 2007). Alternatively, there is a gradual development of PE which varies per person, in terms of the time period (years) in which this change occurs, and also an individual’s awareness or memory of such changes occurring. This might be supported by some participants who were able to describe their feelings changing over time. Additionally, this is only relevant for the five individuals who experienced PE; thus, the small sample size might not clearly capture the potential individual differences (either in memory or awareness) in those who experience PE.

Out of the large range of potential influences of PE, five broad themes were identified. These were: aspects of the person, aspects of the prosthesis, satisfaction with the prosthesis, how the prosthesis is used and how long for, level of conscious awareness of the prosthesis and naturalness/ability of task completion. Identification of such themes is of importance to understanding the different types of influence on PE. Within these themes, many factors previously considered to be of relevance were confirmed (e.g., phantom limb sensations, length of time with prosthesis, and amount of use of prosthesis). One factor of particular interest is the finding that type of prosthesis impacts upon PE, which has implications for both research and rehabilitation. Prior research suggests that incorporation into the body schema only occurs for functional prostheses (Nico et al., 2004) with evidence that purposeful use of a tool extends the arm within the body schema (Giummarra et al., 2008). This might suggest that users of a functional prosthesis might be expected to be more likely to experience PE, however this simple assumption is challenged by some users of such prostheses not experiencing PE. Indeed, tools can be incorporated into the body schema without the subjective aspects of PE, such as a feeling of ownership (de Vignemont, 2011). The finding that one of the two participants who regularly uses a cosmetic prosthesis experienced PE implies that incorporation into the body schema is just one aspect and is not necessary for PE. These findings suggest that other factors might need to be present for a subjective experience of PE to occur.

However, there were also many additional factors which emerged. One of these was identifying a motivational component of PE. This involved individual differences in a desire or need for PE and also potential impact of having a positive mindset towards the prosthesis. Participants who experienced and desired to have PE differed in their reasoning for why they desired to experience PE. Some appreciated the feeling of their prosthesis being embodied, whereas others considered it a less important aspect than other factors such as functionality, whilst acknowledging that PE had positive outcomes for them and so desired it for that reason. For those who did not desire PE, one reason appears to be linked to one of the overall influences of PE – whether the person was born missing their limb or not. Very interestingly and surprisingly, participants differed in whether this encouraged or discouraged PE. For some with congenital limb absence, not having a previous hand to compare the prosthesis to allowed them to embody it, whereas others felt whole before using the prosthesis so did not have a desire for PE. This, highlights the potential motivational aspect along with the influence from body image.

The above motivational factors also may link to the social aspect of PE which emerged, as those with a particularly negative body image may be more sensitive or more aware of negative attention from others. As such attention was found to adversely impact PE, both in a cumulative sense (i.e., overall perceived attention affecting overall level of PE), and temporary sense (i.e., reducing PE at the time of the attention), this suggests the importance of social perception for some users.

Another novel finding was that there were not just positive, but negative outcomes of PE. These involved social aspects, such as having a negative reaction to negative attention from others, for those where the prosthesis feels part of their own body. Body image could be impacted in a negative way, through both the social aspect, but also negative feelings towards the prosthesis (e.g., when broken) being projected towards the user's own body. Such negative factors were impactful in a global sense, with users feeling incomplete without their prosthesis. This was manifested in users potentially feeling restricted in only using one type or specific prosthetic device. These findings have important implications for rehabilitation when considering either to encourage PE, or if the user has naturally embodied their prosthesis.

Overall, aside from the new findings which have emerged, what is clear is that there are a number of discrepancies in what participants reported as important for their experience of PE. In addition to the different ways the prosthesis could be experienced, this included whether individual factors were relevant for PE, whether they encouraged or discouraged PE, and the particular perceived outcomes of PE. Such individual differences were important to identify, but the full realisation of these is a limitation of the qualitative study with a small sample size. Furthermore, generalisations to the larger prosthetics population is not possible with such a method, so it is difficult to determine the overall prevalence of PE or the prevalence of endorsed factors (i.e., which are the factors most associated with PE). In addition, the qualitative study is limited by reliance on self-reported description of experiences which are based on memory or awareness (e.g., whether PE developed gradually over time). This is particularly sensitive because of the small samples typically used in qualitative studies. Thus, a larger study would be beneficial to attempt to avoid some of these potential issues.

In conclusion, the qualitative study identified the complexity of PE involving a much larger range of factors now identified as potentially associated with PE. It also revealed numerous individual differences, and other novel findings involving motivational, social, and negative aspects of PE. Such findings may have implications for rehabilitation, prosthetics design and related psychological research. As a natural logical step, a larger quantitative survey study was developed to further explore PE and associated factors, whilst aiming to rectify some of the limitations of the qualitative study. This study will be detailed in the following chapter.

## **Chapter 4: Survey study on factors associated with embodiment**

In the previous chapter a large range of factors related to the experience of prosthesis embodiment (PE) were identified through interviews. The current chapter details a survey study which aimed to further explore these factors.

Previous research on PE has been somewhat lacking, in particular concerning influences and outcomes. Thus, an in-depth qualitative interviews study with prosthesis users was completed to identify a large range of potential factors which may be associated with upper limb PE. This study found that approximately half of participants reported experiencing PE. Some prosthesis users described their prosthesis as being part of their body or see it is a body part (i.e., integrated into their body image) whereas others described it as connected to their sense of self, and some reported both experiences. Various ways of describing the relationship with the prosthesis were used, including whether the user felt an emotional connection with their prosthesis, describing their feelings using the analogy of an external object worn on the body, feeling natural and not like a foreign object, and whether it felt expendable. Some were suggestibly related to embodiment.

Participants reported experiences suggest they were more likely to be aware of temporary changes in embodiment caused by transient factors, rather than gradual changes over longer periods of time. However, this may relate to their conscious experience or the extent to which they can recall embodiment experiences. One way to clarify this is through collecting quantitative data on the relationship between length of use and embodiment experiences.

The interviews also suggested individual variation in the relative importance of PE to the user, i.e., whether they had a desire or need for their prosthesis to feel part of them, and how important this was for their overall experience of their prosthesis. This raises the question of whether embodiment experiences may be determined by a need or desire for a prosthetic limb to feel like part of the user.

In summary, the qualitative study revealed a much larger range of factors potentially relevant to PE than previously suggested by existing literature. Although the interviews are not able to establish causality, a broad range of potential factors were reported to encourage

or diminish PE, along with a number of potential outcomes of PE being identified. Thus, the study revealed new knowledge which could ultimately potentially benefit rehabilitative services and inform prosthetic design. However, by its nature of being a qualitative sample with a small sample size, it is difficult to generalise these findings to the upper-limb prosthetics population. In addition, only some participants endorsed each factor so is unclear how prevalent each is, or how individual differences might influence the relevance of each factor.

There was minimal suggestion of amputees differing from those with congenital limb absence in terms of PE, however, some specific factors were identified as potentially relevant in terms of encouraging PE (e.g., being born without arm) which differ between the two types of prosthesis user. Such differences may be more apparent with a larger sample which could support comparison between different categories of prosthesis user. Similarly, another broad difference (identified as important from the qualitative study and one of the most highly endorsed influences on PE) is type of prosthesis. It would be useful to see if PE differs based on type of prosthesis overall in a larger sample, as this might reveal a type of prosthesis most likely to provide PE whilst ignoring more variable or idiosyncratic factors.

It is noted that PE has been somewhat conceptualised in the qualitative study as being dichotomous or categorical for analytical purposes (e.g. a factor influencing whether PE occurs or not). However, in reality PE is likely on a continuum and this is reflected by participants' descriptions of how different gradients of embodiment can be experienced, either in terms of developing gradually or a temporary shift in feeling. In addition, there is likely a subjective quality of PE which varies based on the individual. Taking this into account it was considered beneficial to measure PE on a continuum and explore the associations between this and the variety of factors identified as potentially relevant in the qualitative study. Thus, the aim of the detailed study was to explore these potential relationships between various factors and PE in a larger sample, with the information gained hoped to further inform prosthetics design and/or rehabilitation.

The outlined aims were achieved through an anonymous online survey study where both PE and the numerous factors potentially associated with PE were measured. The factors predicted to be associated with PE are presented in Table 7 grouped into broad categories.

Table 7

*Factors predicted to be associated with PE*

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Predicted embodiment factors
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Feelings related to PE
Emotional connection
Feeling indispensable
Feeling foreign
Feeling like glasses analogy
Temporal nature of PE
Gradual changes
Temporary changes
Factors associated with PE
Age of first use
Amount of prosthesis use
Length of time with prosthesis
Type of prosthesis
Type of limb absence
Phantom limb sensation
Phantom limb pain
Phantom limb position
Personal customisation of prosthesis
Number of changes to prosthesis
Desire for prosthesis to feel part of the user
Positive mindset
Body image
Negative attention
Benefits the prosthesis provides
Naturalness of control method
Sensory feedback
Awareness
Planning tasks in advance
Proficiency with prosthesis
Satisfaction with functionality
Satisfaction with appearance
Satisfaction with fitting
Satisfaction with comfort/weight
Satisfaction with reliability
Satisfaction with response speed
Satisfaction with noise
Satisfaction with robustness
Satisfaction with prosthesis overall

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The research questions:

- 1) What proportion of prosthesis users experience feelings of embodiment?
- 2) Is there a relationship between ownership and agency aspects of embodiment?



- H1: There will be a positive association between ownership and agency scores.
- 3) What descriptive terms are used by prosthesis users to describe their embodiment?
- H2: There will be a positive association between emotional connection and embodiment scores.
  - H3: There will be a positive association between feeling indispensable and embodiment scores.
  - H4: There will be a negative association between feeling foreign and embodiment scores.
  - H5: There will be a negative association between feeling like glasses and embodiment scores.
- 4) How is embodiment experienced as changing over time?
- H6: There will be a positive association between gradual changes over time and embodiment scores.
  - H7: There will be a positive association between temporary changes over time and embodiment scores.
- 5) What factors are associated with prosthesis embodiment? – This includes the specific question of does embodiment depend on whether there is a desire for embodiment or not?
- H8: There will be a negative association between age of first use of the prosthesis and embodiment scores.
  - H9: There will be a positive association between amount of prosthesis use and scores.
  - H10: There will be a positive association between length of time with the prosthesis and embodiment scores.
  - H11: Amputees and congenitals will differ on embodiment scores (two-tailed).
  - H12: There will be a difference in embodiment scores based on the type of prosthesis (two-tailed).
  - H13: Those with phantom limb sensations will have lower embodiment scores than those with no phantom limb sensation.
  - H14: Those with phantom limb pain will have lower embodiment scores than those with no phantom limb pain.
  - H15: Those with phantom limbs spatially congruent with their prosthesis will have higher embodiment scores than those with spatially incongruent phantom limbs.
  - H16: Those who have personally customised their prosthesis will have higher embodiment scores than those with no personal customisation.

- H17: There will be a negative association between number of changes to the prosthesis and embodiment scores.
- H18: There will be a positive association between desire for the prosthesis to feel part of the user and embodiment scores.
- H19: There will be a positive association between having a positive mindset towards the prosthesis and embodiment scores.
- H20: There will be a positive association between body image and embodiment scores.
- H21: There will be a negative association between amount of negative attention and embodiment scores.
- H22: There will be a positive association between benefits the prosthesis provides and embodiment scores.
- H23: There will be a positive association between naturalness of control method and embodiment scores.
- H24: There will be a positive association between amount of sensory feedback and embodiment scores.
- H25: There will be a negative association between awareness of prosthesis and embodiment scores.
- H26: There will be a negative association between need for planning tasks and embodiment scores.
- H27: There will be a positive association between proficiency with the prosthesis and embodiment scores.
- H28: There will be a positive association between satisfaction with functionality of the prosthesis and embodiment scores.
- H29: There will be a positive association between satisfaction with appearance of the prosthesis and embodiment scores.
- H30: There will be a positive association between satisfaction with fitting of the prosthesis and embodiment scores.
- H31: There will be a positive association between satisfaction with comfort/weight of the prosthesis and embodiment scores.
- H32: There will be a positive association between satisfaction with robustness of the prosthesis and embodiment scores.
- H33: There will be a positive association between satisfaction with reliability of the prosthesis and embodiment scores.

- H34: There will be a positive association between satisfaction with response speed of the prosthesis and embodiment scores.
- H35: There will be a positive association between satisfaction with noise of the prosthesis and embodiment scores.
- H36: There will be a positive association between satisfaction with the prosthesis overall and embodiment scores.

## **4.1 Method**

**4.1.1 Design.** The acceptance and use of a prosthetic limb is a complicated process (Saradjian et al., 2008) which could be influenced by variation among the unique histories and psychological characteristics of the prosthesis users. A survey design was considered necessary to further develop understanding of the psychology of embodying a prosthetic limb. This approach is most suitable for a large sample of upper-limb prosthesis users to consider and share their experiences with the researcher in relation to them rehabilitating with their prosthesis, including both feelings towards and use of the prosthesis.

### **4.1.2 Sample.**

**4.1.2.1 Inclusion criteria.** Participants included both upper limb amputees and those with congenital limb absence. The limb absence could include either the hand, lower arm, or upper arm. The chosen criteria included that participants needed to have previously owned a prosthesis which they were still using. They had to be over 18 years old, could write in English, and have general access to a website to complete the survey.

**4.1.2.2 Participants.** Multiple power analyses were conducted using G\*Power software (Faul, Erdfelder, Buchner, & Lang, 2009) calculated with a power of .80 and large effect size, to estimate a minimum sample sizes to aim towards. For simple correlations the minimum sample suggested is 23. To compare means of variables compared with a t-test, the minimum sample size suggested is 42. A minimum sample of 30 was sought but, based on recruitment time, as large a sample as possible was aimed for to potentially consider other analyses. The sample consisted of 34 upper-limb prosthesis users who were recruited from online advertisements or were previous contacts who expressed interest in the study. See Table 8 for demographics details of participants.

Table 8

*Details of participants in the sample*

Demographics	
Gender	
Male	21
Female	13
Age range ( <i>M</i> )	20-76 (44)
Number of countries	10*

*Note:* \*Australia, Canada, France, Germany, Ireland, New Zealand, Sweden, Switzerland, United Kingdom, United States.

**4.1.3 Materials.** See Appendix J for ethical approval letter. Materials in the survey included an introductory email to send to sources for advertisement (See Appendix K). This was developed as a standardised email which could be slightly altered if necessary, for an individual source. Two small study advertisements were created for the sources to post, one normal advertisement, and one smaller version developed for Twitter or if a limited advertisement was needed (See Appendix K). The study advertisement contained a direct link to the self-contained survey which was created and held on the Online Surveys tool (formerly ‘Bristol Online Surveys’, <https://www.onlinesurveys.ac.uk/>). This was used as the University held a license to access the survey tool and it was considered suitable for the planned survey. The survey contained numerous sections as follows:

- 1) A PIS (See Appendix L)
- 2) A Consent Form (See Appendix L)
- 3) Instructions for completing the questionnaire (See Appendix L)
- 4) Background information: gender, age, country of residence
- 5) Details of limb absence: Side affected by limb absence, type of limb absence, level of limb absence.
- 6) History of prosthesis use: Details of all prostheses used, age when started using, age when stopped, detail of which prosthesis used the most currently.
- 7) Details of most worn prosthesis: Previous dominant side, number of alterations to the prosthesis, whether it has been personally customised, how much the prosthesis is used in an average day.
- 8) Phantom limb sensations: presence of phantom sensations, phantom limb pain, and spatial position of the phantom limb.

**9) Items measuring embodiment:** This was adapted from a questionnaire by Imaizumi, Asai, and Koyama (2016) by slightly changing the wording on some questions as these were translated from Japanese and needed altering to be more appropriate. Some questions needed some additional information to be clear for users of various types of prosthesis or different types of limb loss, as the original researchers only recruited unilateral amputees. This questionnaire was used as after reviewing any previously published embodiment questionnaires, in particular, focusing on prosthetics, this included items most appropriate to the current study. Additional questions were added to complement those originally used, as identified by review of prosthesis embodiment literature and completion of the qualitative study by the current author. Following Imaizumi et al.'s (2016) original design, questions were split and averaged into composite scores for 'Ownership' and 'Agency' as these have been shown to be discreet components of embodiment in literature. As a reminder, embodiment includes the sub-components body ownership and agency, the feeling of ownership over one's body and the feeling of being the agent of your actions, respectively (de Vignemont, 2011). Whilst ownership and agency are related to each other (de Vignemont, 2007), a dissociation between them has also been found (Kalckert & Ehrsson, 2012), meaning their exact relationship is unclear. Final sub-scales include 7 ownership items and 4 agency items, both measured on a 5-point Likert scale (descriptors vary based on the question, e.g., from *Not at all* to *Entirely*). In addition, both components were averaged to create an overall 'Embodiment' score (See Appendix M).

**10) Factors associated with embodiment:** The questionnaire also includes items measuring potential predictors of embodiment – these include a main response item (e.g., selecting from categories) and importantly, a free-text box if participants wish to clarify their answer (See Appendix M),

**11) Debrief Sheet:** The questionnaire included a final page detailing information about the study and inviting participants to pass on details of the study with anyone of relevance. (See Appendix N).

**4.1.4 Procedure.** Sources for recruitment were contacted via email to request permission from a representative (e.g., webmaster or forum administrator) to post the study advertisement (e.g., on their website or through a newsletter) or to self-post (e.g., on an accessible forum). If the source supported the request, they posted the advertisement in one or more locations (e.g., as a website news item, on a social media account, or included in a newsletter). Alternatively, they gave permission for myself to post (e.g., on a forum). The

advertisement contained a brief description of the research, the researcher's contact details, and a website link to the full self-contained survey. The survey link directed those interested to a full PIS to read and decide if they wished to participate. This also included the research teams' contact details if the participants had any questions before considering participation. Once they decided to participate, an electronic consent form directly following the PIS was completed. Once the questionnaire was completed, this was followed by a Debrief Sheet. A random participant number was generated automatically by the survey and presented on the Debrief Sheet if participants wished to later withdraw their data. The sheet fully informed participants about the aims of the study and asked if happy for their data to be used, along with how they can withdraw from the study. Contact details of the researcher were also provided if they wished to withdraw or have further questions, but otherwise there was no contact between the participant and researcher. At the end of the Debrief Sheet participants were asked to pass the study advertisement or survey link on to any other relevant sources or individuals if they were happy to do so,

**4.1.5 Recruitment sources.** A range of sources were contacted to request advertising the study to prosthesis users. An initial list used in the qualitative study was referred to along with identifying additional sources will be sought and contacted. As NHS ethical approval was not sought these sources did not include rehabilitation centres where participants would be identified because of being an NHS patient, however they did include private prosthetic clinics. Additional sources included amputee charities or organisations which had a website or newsletters/ mailing list to send directly to members, forums/ email discussion lists relevant for prosthesis users, social media groups, independent blogs, relevant online/ printed magazines. A 'snowball' sampling approach was also used by recruitment via word of mouth. This was achieved both from passing on survey details to colleagues in the field (e.g., other researchers) and prosthesis users who complete the survey and decided to pass on to relevant sources or other users (as mentioned on the Debrief Sheet). See Appendix K for a summary of sources contacted and outcomes.

**4.1.6 Ethical considerations.** A broad approach to participant inclusion was adopted where factors of exclusion were limited and the only requirements were that they had an upper-limb amputation or absence and had received a prosthetic limb, could understand and write in English, and have access to the internet to complete the survey. Also, a range of sources were aimed through which to advertise the study. These methods hopefully lead to a

more inclusive and representative sample of upper-limb prosthesis users. Accessibility for prosthesis users has been aimed for by minimising the need to type, with text boxes for typing text optional and only one main question being text-box entry for age. This was hoped to encourage participants to be able to complete the survey, whom will mostly have accessed the advertisement through website links or email, so hopefully would be able to navigate through the survey pages and question responses as they would naturally browse the internet/webpages.

**4.1.7 Analysis.** Data consisted of categorical variables or relationships between variables. For all categorical analyses, assumptions for normality were checked and independent t-tests were conducted. For all relationships between variables, *Spearman's rho* correlations tests were conducted as these are more suitable for ordinal data (i.e., the Likert scale responses).

## **4.2 Results**

Thirty-six participants completed the entire survey (additional participants partially completed it but these were not included). Two participants had to be removed, 1 because they completed every question with the same answer and did not fill in any background information so it was clear this was not an authentic survey completion. The 2nd participant completed background information but noted they had never used a prosthesis.

**4.2.1 Background information.** The following tables for summaries of participant details. Any discrepancies with numbers are due to participant data input errors. See Table 9 for details of limb absence.

Table 9

*Details associated with limb absence*

Limb absence details	<i>n</i>
Limb absence	
Amputee	22
Congenital	12
Unilateral	29
Bilateral	5
Level of limb absence	
The fingers or partial hand	2
At the wrist	4
Below the elbow	20
At the elbow	2
Above the elbow and below the shoulder	7
Below the shoulder but with the shoulder blade intact	1
The shoulder blade and the collar bone	1
Prosthesis on previous dominant hand	
Yes	13
No	17
Ambidextrous	2
Unsure	1

**4.2.2 Embodiment scores.** See Table 10 for summaries of PE scores calculated from averages of the sub-scale scores and overall embodiment score.

Table 10

*Prosthesis embodiment scores summaries*

Embodiment scores	Minimum	Maximum	<i>M</i>	<i>SD</i>
Ownership	1.29	5.00	3.13	1.19
Agency	1.00	5.00	3.57	1.13
Embodiment	1.29	5.00	3.35	1.02

The question of what proportion of prosthesis users experience feelings of embodiment was answered by exploring participants' scores on the 3 embodiment measures. The proportion of participants who scored below and above the middle value was checked to consider how many people experienced low and high embodiment, respectively. For ownership, 19 had low ownership and 15 had high ownership, for agency, 9 had low agency and 25 had high agency, and for embodiment 13 had low embodiment and 21 had high embodiment. The difference in numbers suggests that ownership and to a lesser extent,



embodiment, were somewhat equally split, whereas agency had a greater prevalence of participants scoring highly. The full range of scores on the embodiment scale from 1 (e.g., *Not at all*) to 5 (e.g., *Entirely*) were endorsed by participants with average participants' mean score of ownership, agency, and overall embodiment scores reflecting the middle value of 3. This suggests that participants experienced different levels of PE but when grouped together they averaged around the mid-point of the two extremes (i.e., lowest to highest PE). Extrapolating findings, this might also suggest that in the upper-limb prosthetics population, people, on average, are not experiencing particularly weak or strong PE, but individually this can vary. This was found in the qualitative study with about half experiencing what was identified as PE, with the other half experiencing no PE, but also appreciating that there are potential different gradients of the level of PE subjectively experienced.

In addition, the relationship between ownership and agency aspects of PE was explored. See Figure 12.

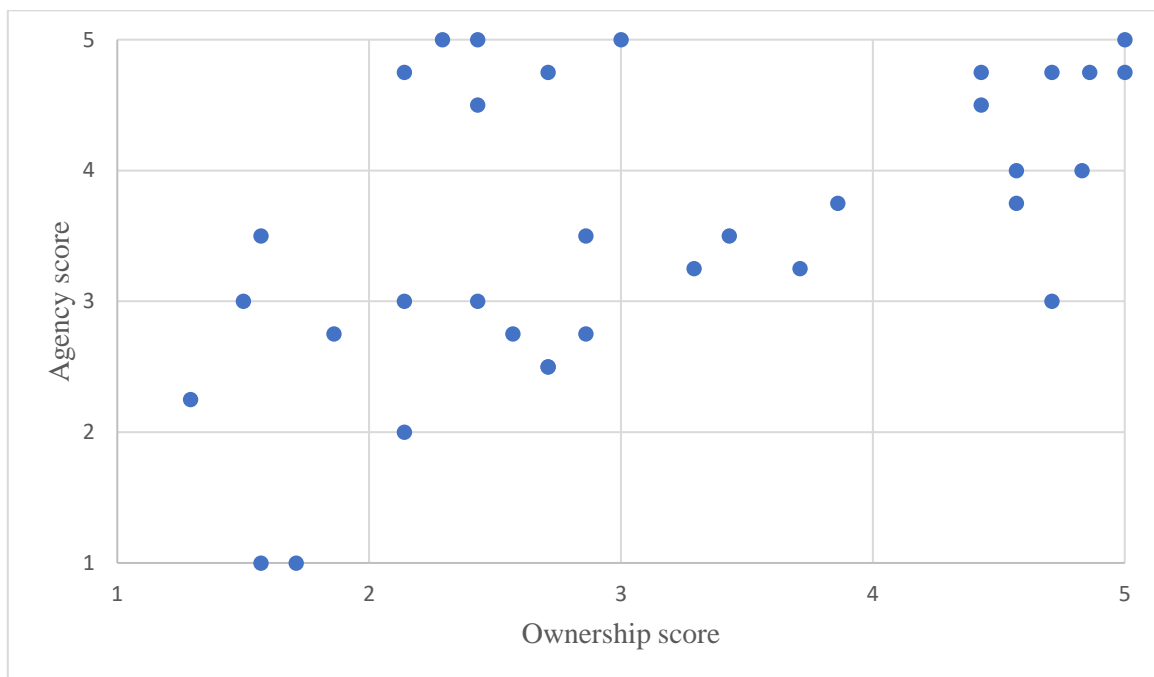


Figure 12. Positive association between ownership and agency scores.

A strong significant positive correlation between ownership and agency was found ( $r_s = .511$ ,  $p = 0.001$ ) suggesting that if participants experienced a stronger sense of ownership then they also had a stronger sense of agency. This highlights the relationship between these components of PE and justifying their aggregation into an overall embodiment score.

**4.2.3 Feelings related to PE.** Certain feelings towards a prosthesis emerged in the qualitative study as potential aspects of PE. These were measured on different gradients of each feeling via a Likert scale response, similar to the embodiment scale and other factors. To explore whether specific feelings reported in the qualitative study are potential further aspects of, or can act as a proxy for PE, these were correlated with PE scores. A Bonferroni correction was applied ( $\alpha \text{ value}/4 = p < .0125$ ) for determining significance. See Table 11 for statistical findings.

Table 11

*Statistical relationships between types of feelings and PE*

Type of feeling	Ownership		Agency		Embodiment	
	$r_s$	$p$	$r_s$	$p$	$r_s$	$p$
Emotional connection	.863	< .001	.546	< .001	.824	< .001
Feels indispensable	.722	< .001	.559	< .001	.739	< .001
Feels foreign	-.679	< .001	-.646	< .001	-.795	< .001
Feels like glasses	-.352	.024	-.343	.027	-.400	.012

Note: Bold = test significant at  $p < .0125$ .

See Figures 13-15 for strong positive relationships between having an emotional connection and all aspects of PE.

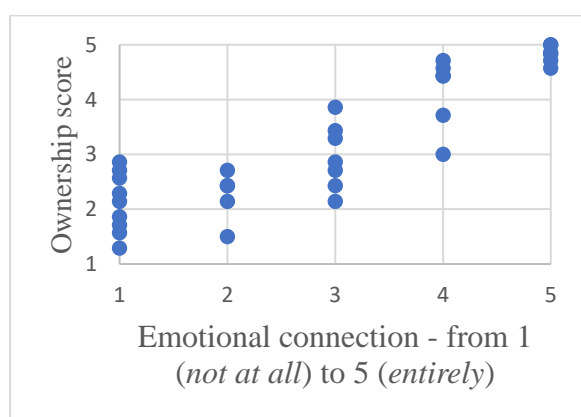


Figure 13. Positive association between emotional connection and ownership.

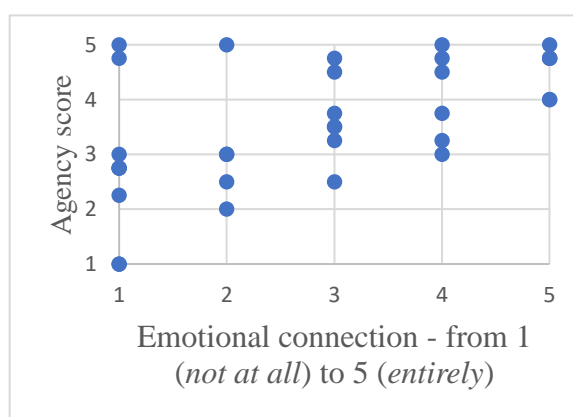


Figure 14. Positive association between emotional connection and agency.

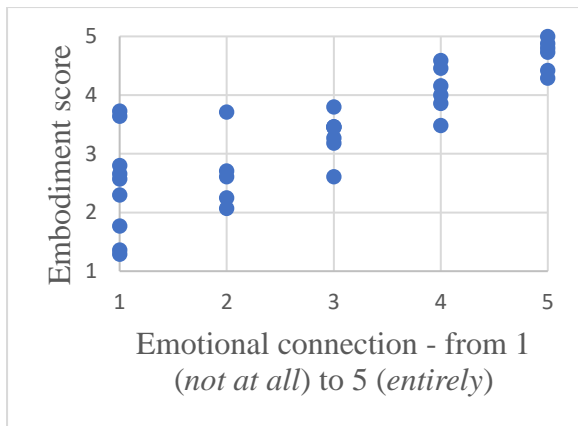


Figure 15. Positive association between emotional connection and embodiment.

From the qualitative study it was revealed that some users felt an emotional connection with their prosthesis whereas others did not. This was not explored as an influence of PE but rather as a specific feeling towards the prosthesis. It was also speculated that this feeling might potentially be considered as an aspect of PE. The current findings support this speculation, suggesting that those who experience PE may have a greater emotional connection with their prosthesis. This perhaps characterises response to a prosthesis as more similar to an anatomical limb than an external tool.

Whether there is an emotional connection or not might be reflected in whether the user considers their prosthesis as indispensable or expendable. Answers to the question of whether users found their prosthesis indispensable also strongly correlated positively with all embodiment scales – see Figures 16-18 for this.

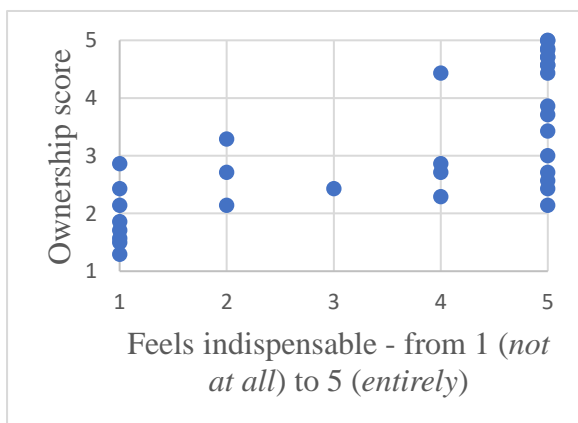


Figure 16. Positive association between feeling indispensable and ownership.

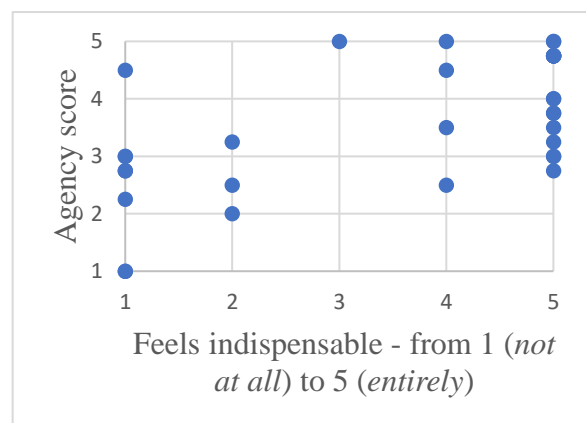


Figure 17. Positive association between feeling indispensable and agency.

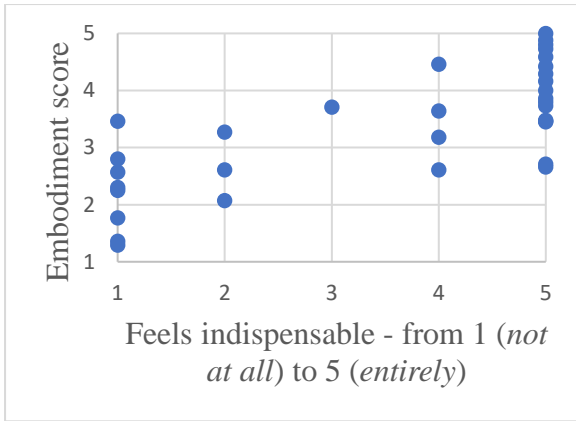


Figure 18. Positive association between feeling indispensable and embodiment.

A prosthesis user who has embodied their prosthesis, in terms of both sense of ownership and sense of agency, may develop a greater connection to their prosthesis. This could result in the user feeling that their prosthesis is indispensable. Similarly, someone who experiences limited or no PE may feel that they would not miss their prosthesis if they had to be without it, thus making it expendable to them. Similar findings were obtained for the question asking whether the prosthesis felt foreign to the participant. Figures 19-21 depict strong negative relationships between these variables.

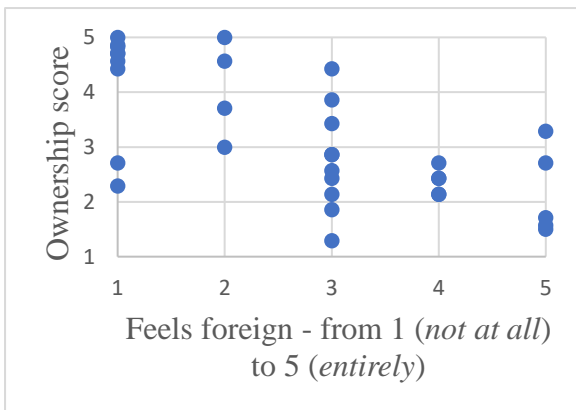


Figure 19. Negative association between feeling foreign and ownership.

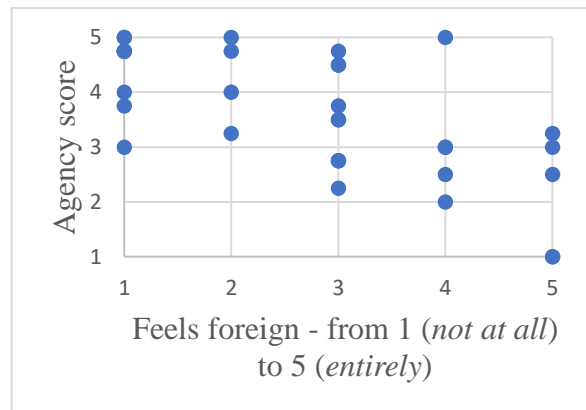


Figure 20. Negative association between feeling foreign and agency.

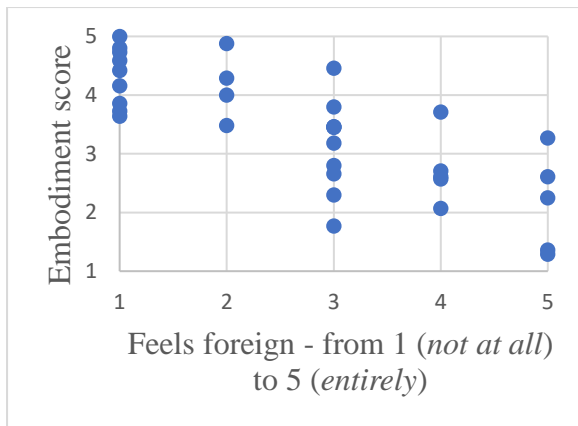


Figure 21. Negative association between feeling foreign and embodiment.

The more foreign a prosthesis feels to the user the weaker sense of embodiment they may experience. The suggestion here is that the naturalness of a prosthesis is potentially a component of PE. If the prosthesis feels more natural to the user, it could be more likely experienced as part of the body rather than an external object. This interpretation was somewhat supported when participants’ scores on how much their prosthesis felt like glasses or other bodily-worn object was moderately correlated with just the overall embodiment score. See Figure 22 for this relationship.

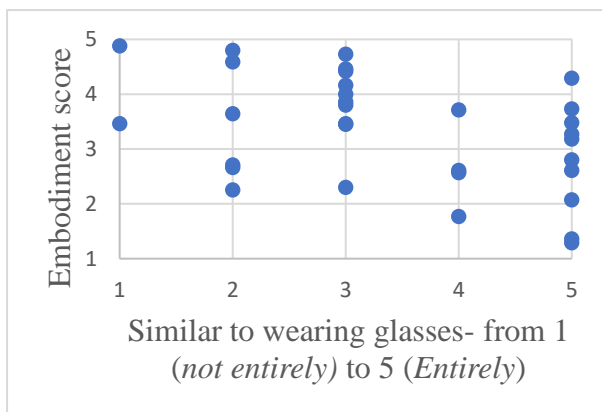


Figure 22. Negative association between feeling similar to glasses and embodiment.

Based on the Bonferroni correction, feeling like glasses was not significantly correlated with ownership ( $r_s = -.352, p = .024$ ) or agency ( $r_s = -.343, p = .027$ ), whilst overall embodiment was marginally significant with a moderate negative correlation ( $r_s = -.400, p = .012$ ). Glasses or other bodily worn items could be somewhat considered as a

foreign object or expendable, but perhaps through repeated wear time they are experienced more as a natural object and not expendable for some. Such people could have weak PE but not compare this to wearing glasses for the above reasons. This might explain why the relationship with ownership and agency were not significant and overall embodiment only just significant. The implication here, is that comparisons made between a prosthesis and wearing glasses may be misleading and potentially not as useful as a measure of PE.

**4.2.4 Temporal nature of PE.** To follow-up on exploring the temporal nature of PE, as highlighted in the qualitative study, participants reported the extent to which their experience of PE either gradually developed and/or fluctuated temporarily. These scores were then correlated with all embodiment measures. See Table 12.

Table 12

*Statistical relationships between temporal changes and PE*

Temporal changes	Ownership		Agency		Embodiment	
	$r_s$	$p$	$r_s$	$p$	$r_s$	$p$
Gradual changes over time	.112	.264	.023	.449	.099	.289
Temporary changes over time	.242	.087	.272	.063	.291	.051

It might be expected that if PE develops over time gradually, then stronger experience of PE would be associated with a greater level of self-reported change over time. No association was found, implying that PE may emerge more rapidly for a user rather than a slow gradual development.

To next answer the question over whether feelings of stronger embodiment are more or less stable (i.e., the amount of fluctuation in overall feelings) the relationship between level of PE and the extent to which such feelings change temporarily was explored. As with changing over time gradually, no such relationships were found (with only overall embodiment approaching significance), suggesting users who experience stronger PE are just as likely to have temporary shifts in embodiment as those with a weaker sense of PE.

The relationship between both temporal factors was also considered, see Figure 23 for this relationship.

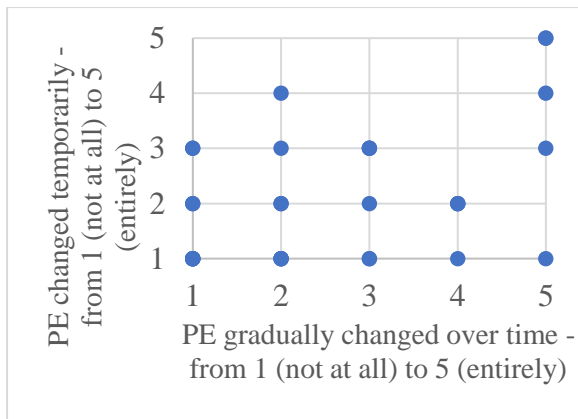


Figure 23. Positive association between PE changing gradually over time and changing temporarily over time.

PE changing gradually over time was found to have a moderate positive correlation with changing temporarily over time ( $r_s = -.382, p = .028$ ), which might suggest that if an individual's PE changes on some temporal level (e.g., changing gradually), then they are likely to change on the other (e.g., temporary change). This might imply that some prosthesis users' sense of PE is more stable in general than others. To consider if any of the overall factors predicted to be associated with PE were also related to temporal changes in PE, such factors were correlated with both temporal variables. The only significant associations found were with amount of negative attention being positively related to gradual change over time ( $r_s = .448, p = .009$ ), and satisfaction with noise being negatively correlated with temporary changes over time ( $r_s = -.350, p = .046$ ). The former suggests that greater perceived negative attention is somehow related to feelings of PE changing over a period of time. Notably, the item asking about feelings of PE changing over time did not specify in which direction PE had changed (i.e., whether it developed or reduced over time). Previous understanding of gradual changes over time had assumed that PE gradually develops, however it is possible that someone could experience PE and then environmental aspects (e.g., increasing amount of perceived negative attention) could have gradually reduced this experience. Alternatively, if PE has gradually developed, perhaps individuals become more aware of negative attention because they consider the prosthesis as part of them, thus negative attention is even more salient (i.e., negative attention is towards them rather than their prosthesis). Satisfaction with noise negatively correlating with temporary changes, suggests that being dissatisfied with noise might influence PE temporarily changing. The impact of noise being a disruptive factor to embodiment was mentioned by one participant in the qualitative study (rather than as a form of useful sensory feedback, as mentioned by another participant). This finding could

suggest that, in the moments that the prosthesis is making noises which the user is unhappy with, their PE is temporarily reduced.

**4.2.5 Factors related to PE.** The following section details factors related to PE including associations measured with Spearman’s rho and categorical differences measured with t-tests and an ANOVA. Factors have been grouped into separate categories for descriptive purposes.

**4.2.5.1 Aspects of limb absence.** A number of factors identified as being relevant for PE in the qualitative study were relating to limb absence. These include: type of limb absence, phantom limb sensations, phantom limb pain, and phantom limb position. For all of these variables, differences in embodiment scores (ownership, agency, and overall embodiment scores measured separately) were compared /between the respective levels of the category. All categories were explored with independent t-tests except for type of prosthesis, which was analysed with a one-way ANOVA. A Bonferroni correction was applied (alpha value/4 =  $p < .0125$ ) for determining significance for the t-tests. All tests were one-tailed except for type of limb absence which was two-tailed due to it being unclear whether amputees or those with congenital limb absence would have higher embodiment scores. See Table 13 for statistical findings from comparisons of embodiment scores made within numerous categories.

Table 13

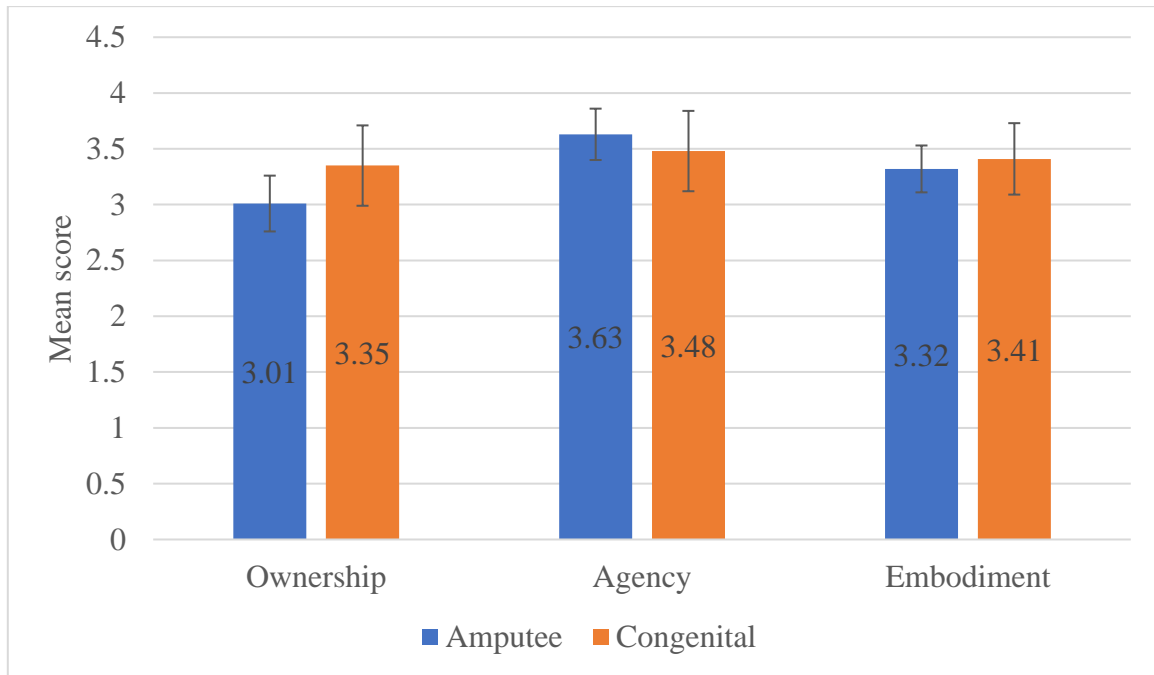
*Statistical differences in embodiment scores across aspects of limb absence*

Aspect of limb absence	Ownership		Agency		Embodiment	
	<i>t (df)</i>	<i>p</i>	<i>t (df)</i>	<i>p</i>	<i>t (df)</i>	<i>p</i>
Type of limb absence	-0.781(32)	.440	0.356 (32)	.724	-0.260(32)	.797
Phantom limb sensations	1.319(30)	.099	0.325(30)	.374	.946(30)	.176
Phantom limb pain	-2.648(20)	<b>.008</b>	-1.425(20)	.085	-2.371(20)	.014
Phantom limb position	1.640(24)	.057	1.338(24)	.097	1.770(24)	.045

*Note.* Bold = test significant at  $p < 0.0125$ .



Whether limb absence was due to congenital limb absence or amputation was considered relevant for PE based on findings from the qualitative study. See Figure 24 for comparison between amputees and those with congenital limb absence (referred to as congenitals).



*Figure 24.* Mean scores for ownership, agency, and embodiment compared between type of limb absence (amputees and congenitals), with error bars representing the Standard Error.

As shown in Figure 24, amputees and congenitals did not significantly differ in all embodiment scores, with only slightly higher scores for congenitals. This suggests that whether a person's limb absence is from birth or due to a later amputation does not have an overall influence on how well the prosthesis is embodied.

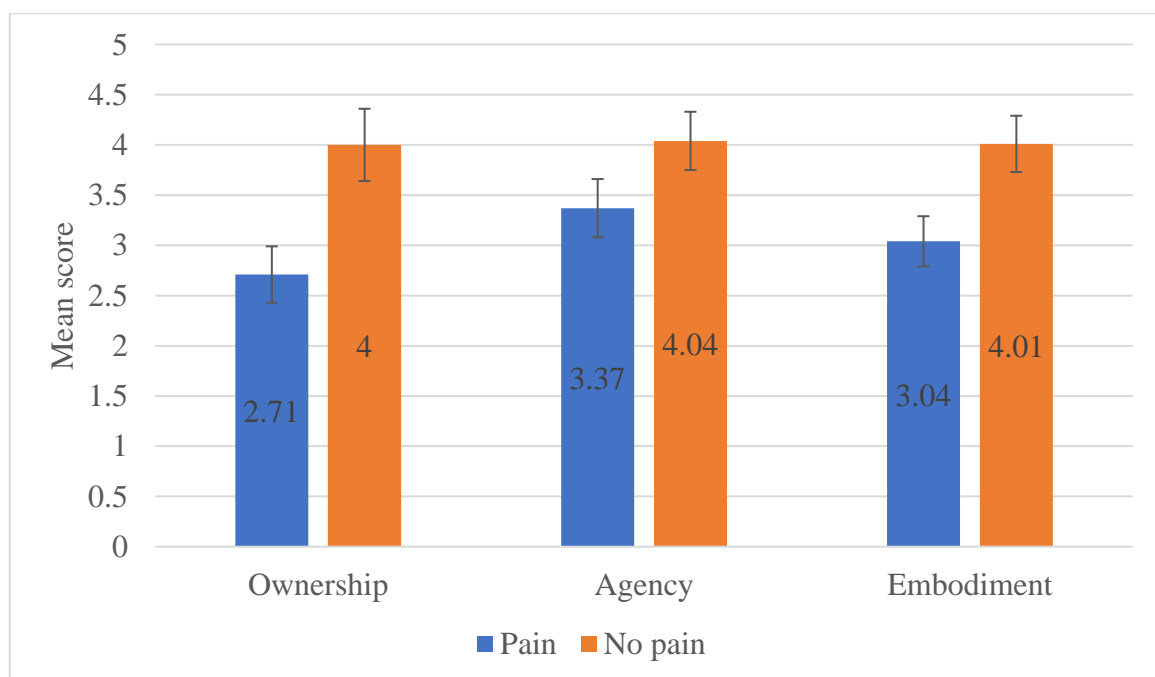
See Table 14 for details of phantom limb sensations for most currently worn prosthesis.

Table 14

*Frequencies of phantom limb sensations*

Phantom limb details	<i>n</i>
Phantom limb sensations with currently most worn prosthesis	20
Phantom limb pain experienced during currently most used prosthesis	20
Phantom limb sensation corresponds with position of prosthesis	5

The presence or absence of phantom limb sensations was explored to see if this had any overall impact on embodiment scores. Whilst having phantom sensations raised embodiment scores on all scales, no difference was significant. This suggests that all aspects of PE could be experienced by prosthesis users similarly irrespective of whether the person has phantom sensations or not. However, the influencing factor on embodiment may not be sensations per se, but rather whether they are painful or experienced in a position incongruent to the prosthesis. See Figure 25 for comparison of scores based on whether the participant experienced any phantom limb pain.



*Figure 25.* Mean scores for ownership, agency, and embodiment compared between presence or absence of phantom limb pain, with error bars representing the Standard Error.

Ownership was found to be significantly higher for those who had no PLP. This potentially suggests that experiencing pain in roughly the location of the prosthesis might disrupt feeling ownership for prosthesis users. Whereas, the feeling of agency can still persist if there is pain present.

Whilst the presence of pain could influence PE, the exact position of the pain might have a mediating effect on whether this disrupts embodiment of the prosthesis. However, when the spatial correspondence of the phantom sensations and the prosthesis (i.e., whether the phantom was experienced roughly in the position of the prosthesis or not) were compared, no differences were found. Despite this, all embodiment scores were higher when the phantom corresponded with the prosthesis, suggesting that at least for some prosthesis users this might help encourage PE. In addition, some participants were unsure, making the 2 comparison groups small which might mask any potential differences between the groups.

**4.2.5.2 Type of prosthesis.** The following tables display summaries for the most currently worn prosthesis. See Table 15 for frequencies for each type of prosthesis.

Table 15

*Frequencies of type of prosthesis most currently worn*

Type of prosthesis	<i>n</i>
Cosmetic	8
Body-powered	14
Myoelectric	12

The overall type of prosthesis (cosmetic, body-powered, or myoelectric) was previously reported in the qualitative study to have an influence on PE. See Figure 26 for comparison between the three types of prosthesis.

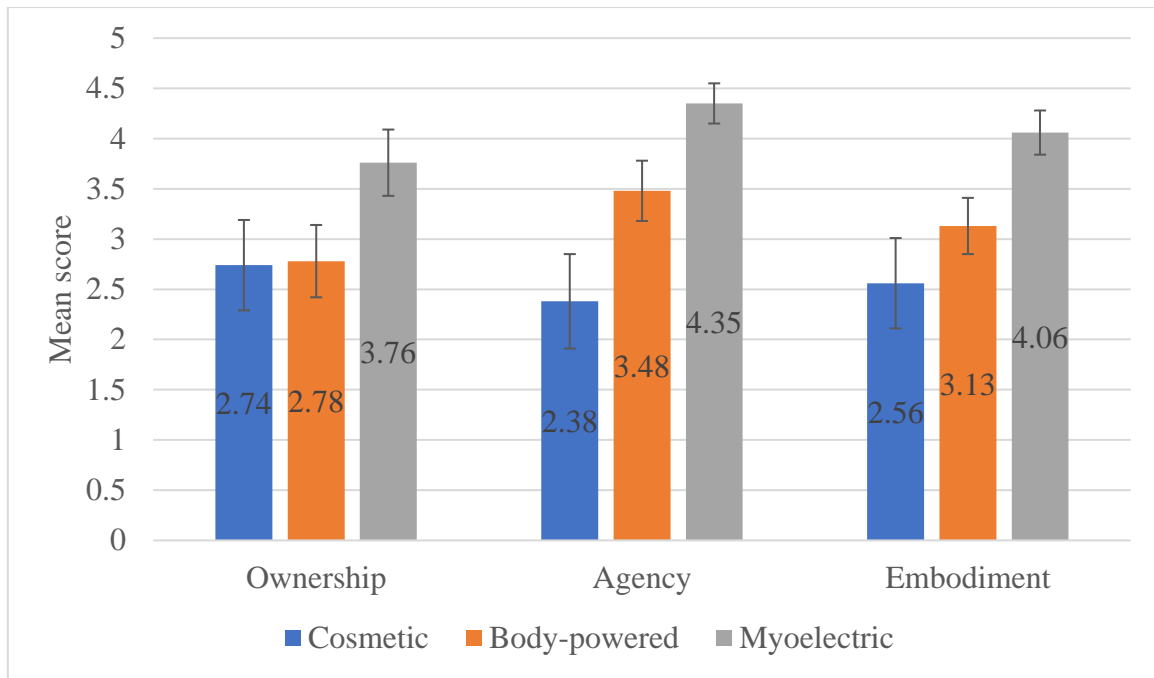


Figure 26. Mean scores for ownership, agency, and embodiment compared between type of prosthesis, with error bars representing the Standard Error.

Ownership did not differ between prosthesis type ( $F(2,26) = 2.641, p = .111$ ) and this was generally supported by Bayesian analysis ( $BF_{10} = 0.839$ ), which provided weak evidence for the null hypothesis; however, agency and embodiment did differ, ( $F(2,26) = 9.360, p = .001, \eta^2 = 0.419$ ) and ( $F(2,26) = 6.354, p = .006, \eta^2 = .328$ ), respectively. Through Tukey post-hoc comparisons it was found that there was an agency difference between cosmetic and body-powered prostheses approaching significance ( $p = .066$ ). This was supported by Bayesian analysis ( $BF_{10} = 1.590$ ), providing weak evidence for the alternative hypothesis. Myoelectric prosthesis users scored significantly higher than cosmetic users ( $p = .001$ ), supported by Bayesian analysis ( $BF_{10} = 71.701$ ), providing strong evidence in favour of the alternative hypothesis, but body-powered and myoelectric prosthesis users did not differ ( $p = 0.078$ ). However, Bayesian analysis ( $BF_{10} = 2.765$ ), provided weak evidence for the alternative hypothesis, with the data being 2.765 times more likely with the alternative compared to null hypothesis. These findings suggest that overall, body-powered and myoelectric prosthesis users are equally likely to experience a certain level of agency over their prosthesis but some myoelectric users may experience a stronger sense of agency. However, the findings more clearly suggest that myoelectric prosthesis users might experience stronger agency than cosmetic users. This might be expected with the functional control of a myoelectric prosthesis affording a greater experience of agency compared to a

non-functional cosmetic prosthesis. The observed potential difference for body-powered prostheses compared to cosmetic prostheses also fits with this interpretation, with the difference not reaching significance due to the small sample size. This is perhaps supported by the Bayesian analysis providing weak support for a difference. Whereas, both myoelectric and body-powered prostheses are functional so a user could equally feel a sense of agency over the limb, supported by no significant difference but with some suggestion of increased agency for some myoelectric users.

Similarly, for embodiment the difference was found between cosmetic and myoelectric users ( $p = .007$ ), no difference between cosmetic and body-powered users ( $p = .433$ ), but the difference between body-powered and myoelectric prostheses was approaching significance ( $p = .051$ ). This suggests that cosmetic and body-powered users are equally likely to have a stronger experience of overall PE, as the specific importance of agency differentiating these types is absent here, being combined with ownership. However, as with agency, it suggests that myoelectric prosthesis users are more likely to experience stronger PE, but whereas myoelectric and body-powered users could feel a similar sense of agency, there is suggestion here that myoelectric users could potentially have stronger overall PE than body-powered users. Overall, the order of magnitude between the prosthetic types (i.e., cosmetic the weakest and myoelectric the strongest) for both agency and embodiment was also matched for ownership, despite no significant differences suggesting how all aspects of embodiment could be experienced differently based on prosthesis type used.

**4.2.5.3 Changes to the prosthesis.** Whether a prosthesis was personally customised in terms of visual appearance was found to have no influence on ownership ( $t(32) = 0.615, p = .272$ ), agency ( $t(32) = 0.527, p = .301$ ), or embodiment ( $t(32) = 0.654, p = .259$ ). Whilst this was raised as an important influence on PE in the qualitative study, it was however only mentioned by one participant. Interestingly, in the current study there was roughly an equal split of those with or without a personally customised prosthesis. One interpretation is that the relevance of this for PE depends on the individual. This means that overall the two groups might not differ on PE, but for some people it is a factor of influence. Whilst personal customisation did not appear related to embodiment scores, how much a prosthesis had been altered in general was also explored. See Figures 27-29 for the relationship between number of changes to the prosthesis and embodiment scores – 3 outliers (1 number of changes at 50 and 2 at 99) have been removed from graphs for optimal presentation.

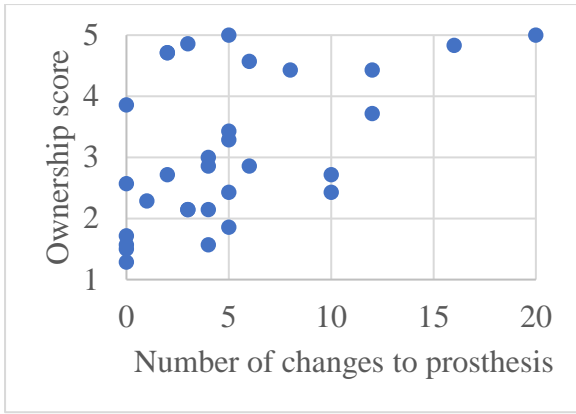


Figure 27. Positive association between number of changes to prosthesis and ownership.

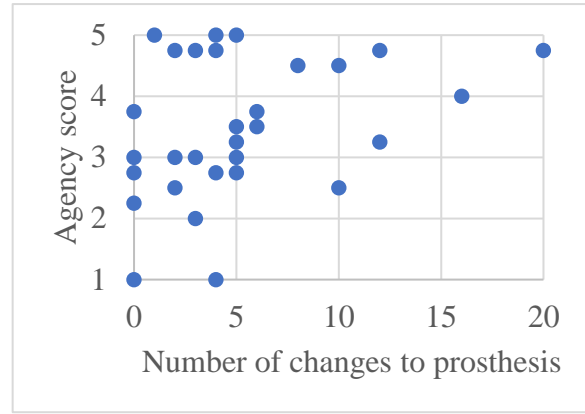


Figure 28. Positive association between number of changes to prosthesis and agency.

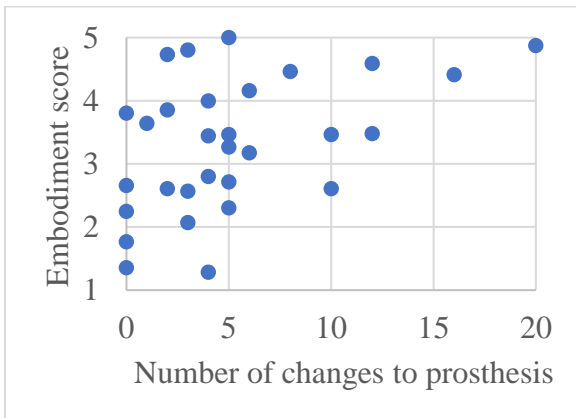


Figure 29. Positive association between number of changes to prosthesis and embodiment.

As Figures 27-29 suggest, a moderate positive relationship was found between number of changes to the prosthesis and ownership ( $r_s = .424, p = .007$ ), agency ( $r_s = .398, p = .010$ ), and embodiment ( $r_s = .462, p = .003$ ). This suggests those who had a greater number of changes to their prostheses encouraged all aspects of embodiment, when the opposite was expected. One explanation might be that instead of disrupting PE, multiple changes might have improved the prosthesis, ultimately leading to a stronger sense of embodiment.

**4.2.5.4 Use and time.** A group of factors centred on aspects of use of the prosthesis and time with the prosthesis were explored in terms of their relationship with PE. See Table 16 for a list of these and the statistical findings.

Table 16

*Statistical relationships between aspects of use and time and PE*

Aspect of use and time	Ownership		Agency		Embodiment	
	$r_s$	$p$	$r_s$	$p$	$r_s$	$p$
Age of first use	.027	.443	.170	.177	.074	.344
Amount of prosthesis use	.591	< .001	.664	< .001	.715	< .001
Length of time with prosthesis	.063	.369	.137	.232	.089	.317

Note: Bold = test significant at  $p < .05$ .

Using a prosthesis from an early age was identified as being important for PE by some users in the qualitative study. However, when age of first use was explored in relation to PE here, no relationships were found, suggesting that the age when a prosthesis is first used from does not have a significant impact on the amount of PE ultimately experienced. Next, how much a prosthesis has been used will be considered. See Table 17 for categories of amount of daily usage of the prosthesis and the number of participants for each time band.

Table 17

*Amount of daily use of prosthesis*

Hours of daily prosthesis use	$n$
0-4	11
4-8	4
8-12	8
12-16	8
16-20	3

In contrast to age of first use, the amount of prosthesis use had a strong positive relationship with ownership, agency, and embodiment. Scatterplots for embodiment measures can be seen below in Figures 30-32. Numbers 1 (0-4 hrs) to 5 (16-20 hrs) represent the different time bands above.

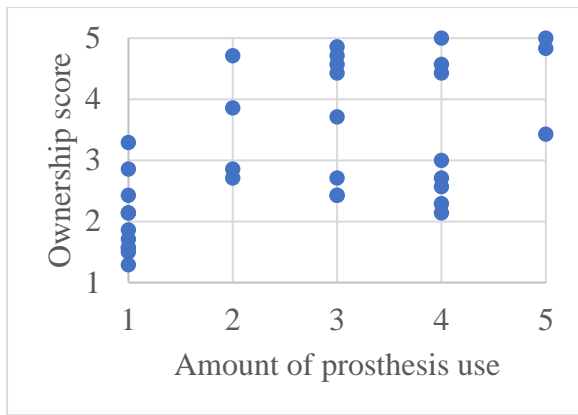


Figure 30. Positive correlation between amount of prosthesis use and ownership

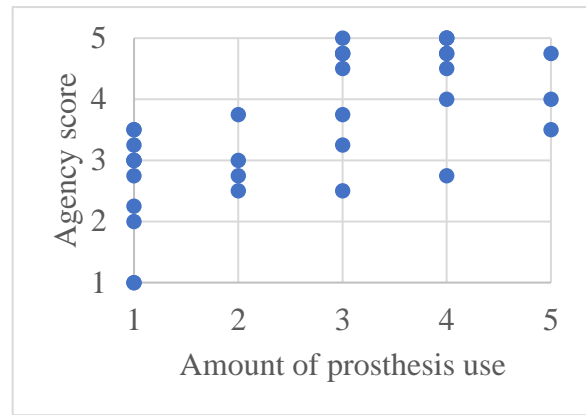


Figure 31. Positive correlation between amount of prosthesis use and agency

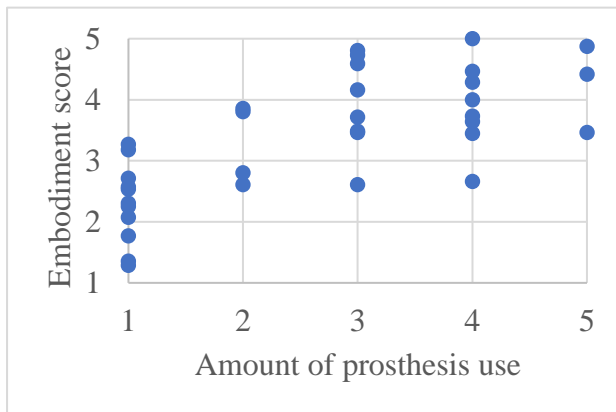


Figure 32. Positive association between amount of prosthesis use and embodiment.

For all embodiment measures, moderate to strong correlations were found. This suggests that the more someone uses their prosthesis (on an average day) the more they will experience PE overall. Greater use of a prosthesis could enable the user to get used to their prosthesis, both in terms of overall feeling and learning ways to use the prosthesis for specific tasks. The former may result in a reduced conscious awareness of the prosthesis and the latter a greater proficiency. In addition, proficiency could also contribute to a reduced awareness. Both of these aspects are discussed further later.

Interestingly, when just looking at the relationship between length of time (instead of amount of use) with embodiment measures, no significant relationship was found for ownership, agency, and embodiment. This suggests that how much a prosthesis is used on an average day, not how long the prosthesis has been owned for, could influence PE. This lack



of relationship might be explained by PE not gradually developing over time for some users (as highlighted by no significant correlation found between PE and gradual changes over time). For example, someone may have limited PE due to a variety of other factors, irrespective of how long they have had their prosthesis for.

**4.2.5.5 Motivational aspects.** To further explore whether motivational aspects, as potentially suggested in the qualitative study, both desire for PE and having a positive mindset were correlated with embodiment measures and with each other. See Table 18 for the statistical findings.

Table 18

*Statistical relationships between motivational aspects and PE*

Motivational aspect	Ownership		Agency		Embodiment	
	$r_s$	$p$	$r_s$	$p$	$r_s$	$p$
Desire for it to feel part of them	.722	< .001	.245	.081	.597	< .001
Positive mindset	.477	.003	.197	.139	.455	.006

Note: Bold = test significant at  $p < .05$ .

A strong positive relationship was found between ownership and embodiment with having a desire for the prosthesis to feel part of the user, whereas no relationship was found for agency. See Figures 33-34 for scatter graphs of these relationships.

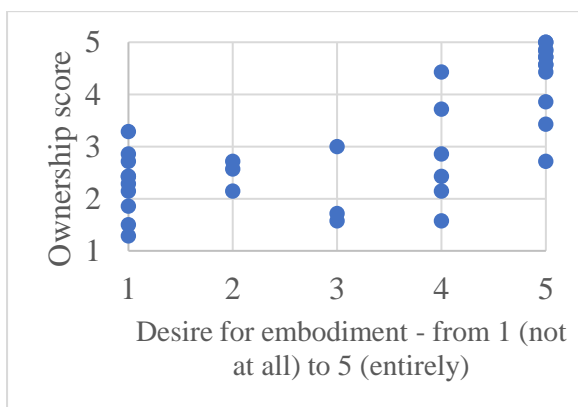


Figure 33. Positive association between desire for embodiment and ownership.

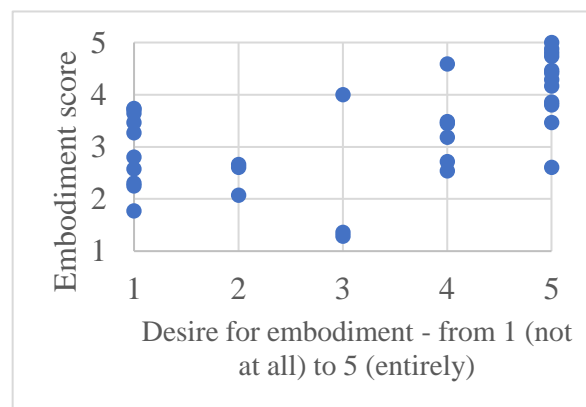


Figure 34. Positive association between desire for embodiment and embodiment.

There are likely to be individual differences in desire for PE, with this being a lower priority for some. Indeed, some may not wish for their prosthesis to feel part of them, if they understand its limitations and just want the prosthesis to aid functionality as a tool, rather than act as a replacement limb. This perhaps explains the lack of relationship with agency, as some users may feel in control of their prosthesis, similar to agency over a tool, yet have no desire for other aspects of PE, such as feeling ownership over the prosthesis. The relationship with ownership (and consequently likely causing the overall embodiment relationship) could be interpreted differently. Either, having a desire for PE encourages ownership in some way (e.g., through persevering with the prosthesis), or having feelings of ownership makes the desire for PE (e.g., through benefits of sense of ownership) salient to the person.

One additional individual difference in feelings towards their prosthesis is whether the person has a positive mindset in terms of being a successful prosthesis when learning to use it. See Figures 35-36 for strong associations between positive mindset and ownership and embodiment.

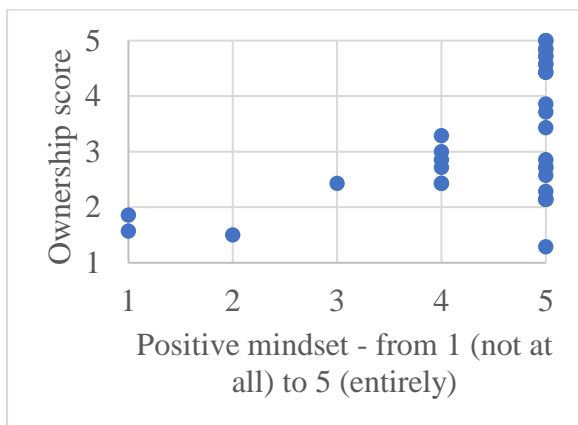


Figure 35. Positive association between positive mindset and ownership.

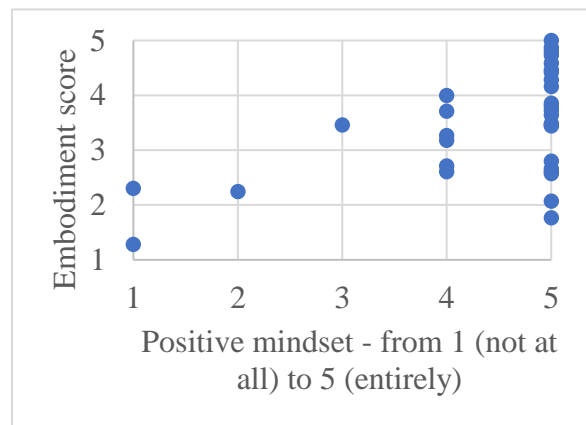


Figure 36. Positive association between positive mindset and embodiment.

Having a positive mindset towards being successful with a prosthesis during initial use can potentially encourage a stronger sense of PE. Whilst the data is correlational, greater confidence perhaps can be placed on this acting as an influence rather than outcome. This is due to the question focusing on determination during initial use rather than having an overall positive mindset. Having a positive outlook in the face of numerous challenges adapting to prosthesis use could help a prosthesis user to persevere with their prosthesis where it gradually becomes part of them.

**4.2.5.6 Social aspects.** As mentioned in the qualitative study, social aspects may influence PE and potential links were drawn between how positive body image is perceived to be and the perceived amount of negative attention received from others, and how they might impact a person’s embodiment of their prosthesis. See Table 19 for statistical relationships.

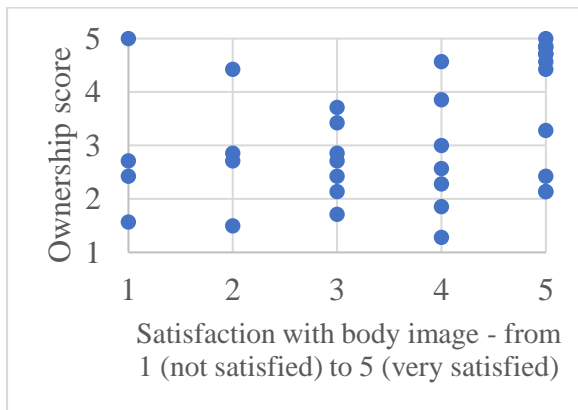
Table 19

*Statistical relationships between social aspects and PE*

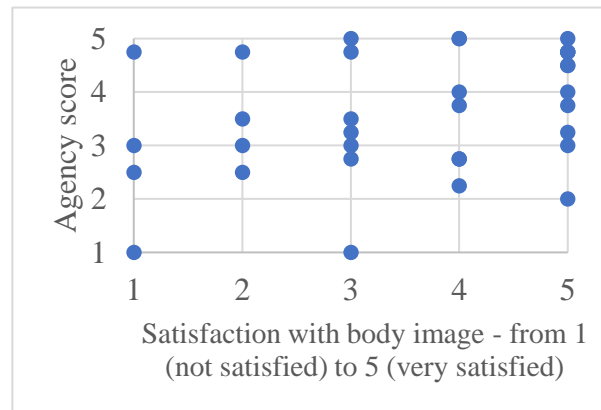
Social aspect	Ownership		Agency		Embodiment	
	$r_s$	$p$	$r_s$	$p$	$r_s$	$p$
Body image	.312	<b>.039</b>	.303	<b>.043</b>	.381	<b>.015</b>
Amount of negative attention	.059	.371	.085	.319	.118	.258

*Note:* Bold = test significant at  $p < .05$ .

How positive or negative someone feels towards their body image was considered as potentially relevant for PE. See Figures 37-39 for moderate positive relationships found between body image and PE.



*Figure 37.* Positive association between body image and ownership.



*Figure 38.* Positive association between body image and agency.

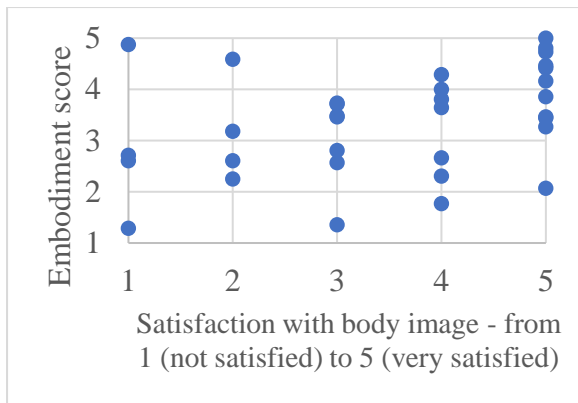


Figure 39. Positive association between body image and embodiment.

The findings suggest that either having a more positive body image leads towards a greater sense of PE (i.e., an influence of PE), or alternatively that experiencing greater PE leads to a more positive body image as a result (i.e., an outcome of embodiment). Both of these were explored in the qualitative study as potentially relevant, despite only being endorsed in a limited capacity. Whilst there were some potentially conflicting findings with how body image might specifically influence PE, there appeared a clearer justification for stronger PE improving a user’s body image. However, unfortunately the exact direction of the relationship is unclear from this survey study and a different experimental design would be needed to determine causality (i.e., a technique to induce PE and then measure whether body image has improved).

Potentially linked to how a user feels towards their body image is how much negative attention they perceive from others towards their prosthesis. In the qualitative study this perception of having a greater amount of negative attention was reported as an influence on PE in terms of reducing it, both overall, and as a temporary influence. This was explained as the user’s feeling of acceptance of their prosthesis being partly due to how others were viewing them and reacting to their prosthesis. In contrast to this, no such relationship was found in the survey study. This perhaps suggests an individual difference in how much negative attention by others can influence a person’s feelings towards their prosthesis. Some could experience limited negative attention but still not embody their prosthesis with others experiencing greater negative third-party attention but feel proud of their prosthesis and have stronger PE. It might only be a limited number of users whose awareness of others’ viewpoints ultimately or significantly influences their own feelings towards their prosthesis.

**4.2.5.7 Control factors of the prosthesis.** A group of factors centred on aspects of controlling the prosthesis were explored in terms of their relationship with PE. See Table 20 for a list of these and the statistical findings.

Table 20

*Statistical relationships between control factors of the prosthesis and PE*

Control factor	Ownership		Agency		Embodiment	
	$r_s$	$p$	$r_s$	$p$	$r_s$	$p$
Benefits the prosthesis provides	.593	< .001	.676	< .001	.735	< .001
Control method	.522	.001	.688	< .001	.711	< .001
Sensory feedback	.528	.001	.402	.011	.586	< .001
Awareness of prosthesis	-.244	.090	-.416	.009	-.404	.011
Need for planning tasks	-.250	.084	-.313	.041	-.311	.042
Proficiency with prosthesis	.383	.015	.771	< .001	.632	< .001

Note: Bold = test significant at  $p < .05$ .

The strong positive relationship between amount of benefits perceived to be provided by a prosthesis and all aspects of PE are shown in Figures 40-42.

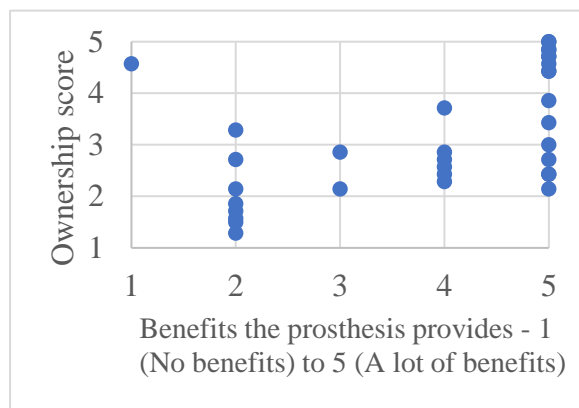


Figure 40. Positive association between benefits which the prosthesis provides and ownership.

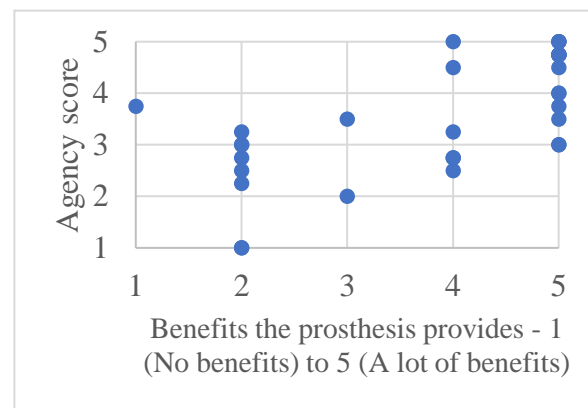


Figure 41. Positive association between benefits which the prosthesis provides and agency.

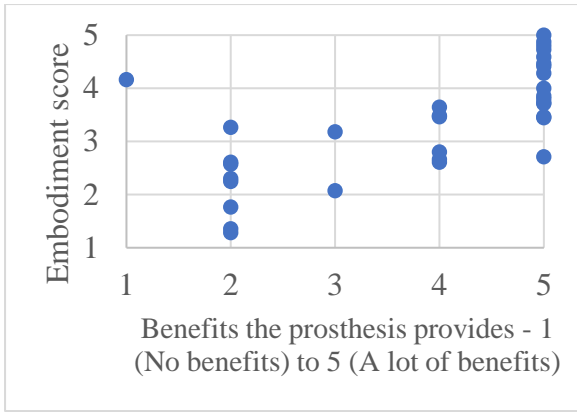


Figure 42. Positive association between benefits which the prosthesis provides and embodiment.

If a prosthesis user perceives having a greater level of benefits from using their prosthesis then they may subsequently consider it more as part of them. This is of course only to be expected. However, it is unclear here what exact benefits contribute most towards PE. Also, there is the chance that PE instead leads to perceiving a greater number of benefits, due to feeling positive towards their limb and having a greater appreciation of the benefits it provides them with.

As highlighted in Figures 43-45, the perceived ‘naturalness’ of control method of the prosthesis had a strong association with PE.

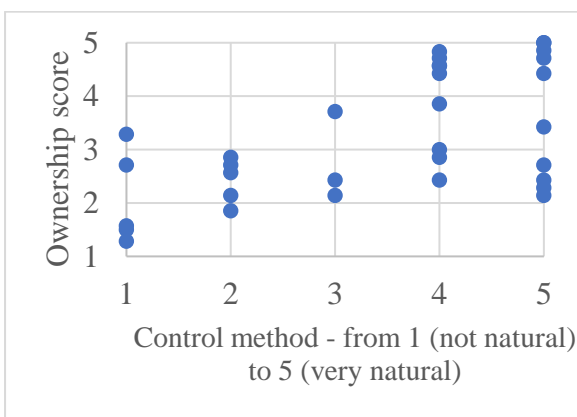


Figure 43. Positive association between natural control method and ownership.

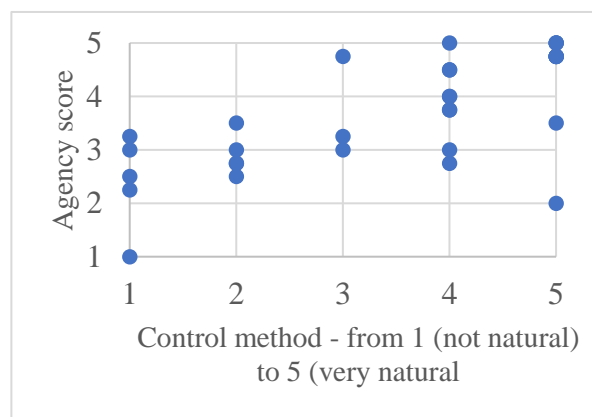
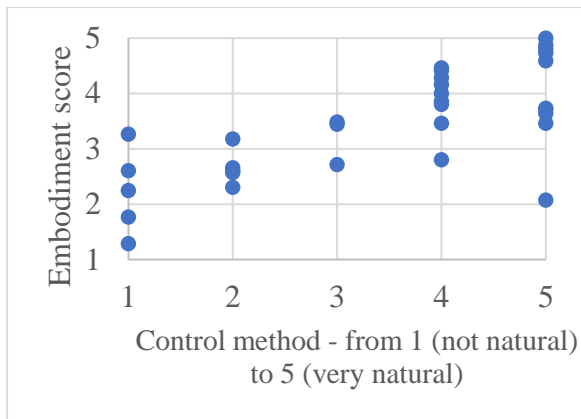


Figure 44. Positive association between natural control method and agency.



*Figure 45.* Positive association between natural control method and embodiment.

The more natural a prosthesis feels in terms of controlling it, the greater the chance that it will feel part of the user. This is reflected in interviews from the qualitative study, where some interviews reported the unnatural control method of either a body-powered or myoelectric prosthesis made the prosthesis feel not part of them. Alternatively, the relationship found in the current study could be due to users reporting their prosthesis feeling more natural in general (compared to the actual control method). If so, this could be caused by the presence of PE. Causality cannot be determined here, so a different experimental approach would be beneficial to explore this further.

The presence of sensory feedback provides the user with additional senses coming from their prosthesis, thus providing additional information that the limb is their own. As would be expected from this, moderate to strong associations between amount of sensory feedback and PE were found, see Figures 46-48.

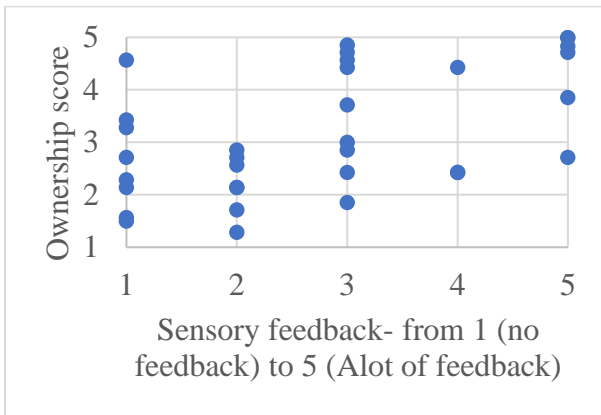


Figure 46. Positive association between sensory feedback and ownership.

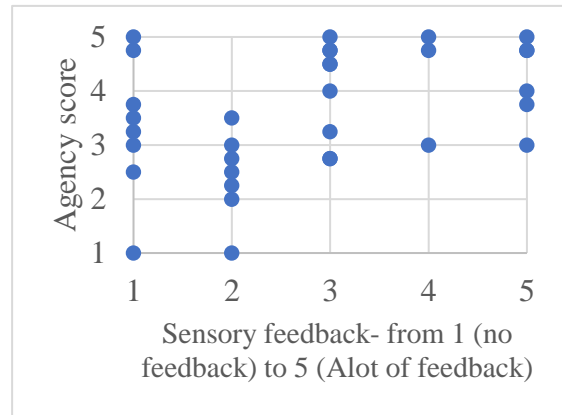


Figure 47. Positive association between sensory feedback and agency.

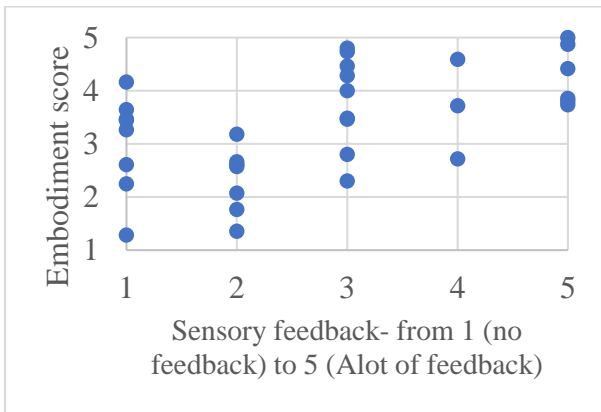


Figure 48. Positive association between sensory feedback and embodiment.

See Figures 49-50 for moderate negative correlations between awareness of prosthesis and agency and embodiment.



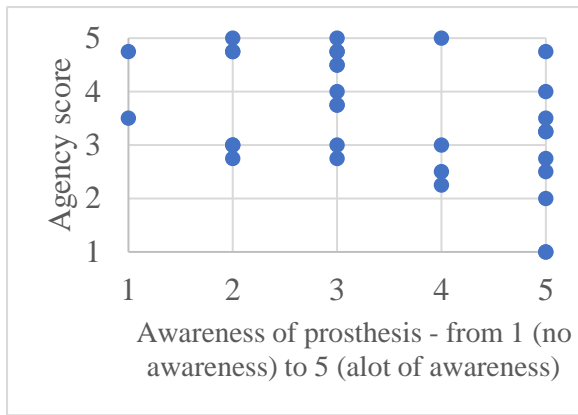


Figure 49. Negative association between awareness of prosthesis and agency.

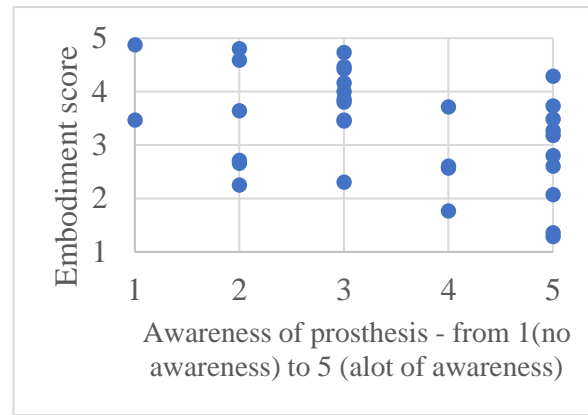


Figure 50. Negative association between awareness of prosthesis and embodiment.

The negative relationship with agency (and hence overall embodiment relationship) suggests that those who have a greater conscious awareness of their prosthesis feel like they less in control of their actions with the prosthesis. This might be due to some users having issues with control of their prosthesis, drawing greater attention to it and subsequently reducing their feeling of control over the prosthesis. Alternatively, if the prosthesis does not feel part of the user, in terms of not feeling in control of it, this might attract an increased amount of attention towards the prosthesis. However, the lack of relationship between awareness and ownership was unexpected as there was suggestion this might either be an influence or outcome of feeling ownership.

See Figures 51-52 for moderate negative correlations between need for planning tasks in advance and agency and embodiment.

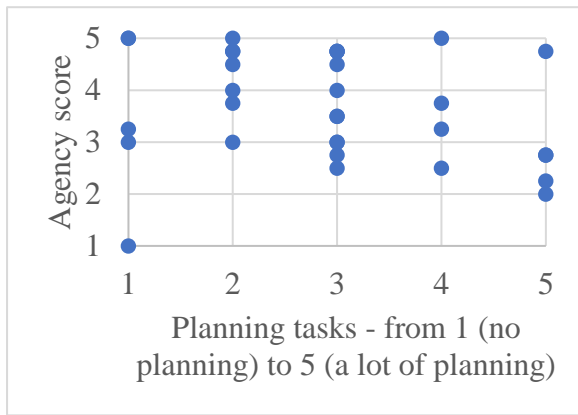


Figure 51. Negative association between need for planning tasks in advance and agency.

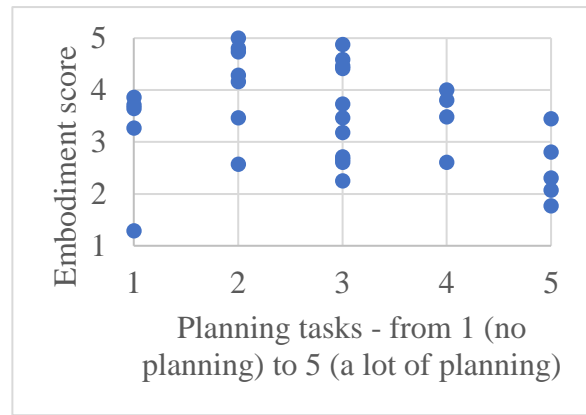


Figure 52. Negative association between need for planning tasks in advance and embodiment.

The negative relationships found were as expected for agency and overall embodiment, although this was not found for ownership. The findings suggest that with a greater need to plan specific tasks, rather than carry them out automatically (or without some planning before beginning an action), there is a reduced sense of agency over the prosthesis. Such planning might subsequently make the user feel like they don't have complete control over their prosthesis to carry out tasks naturally. Another interpretation is that having a reduced or lack of agency over the prosthesis causes the person to feel unconfident in task completion and hence require further planning. Both interpretations highlight the specific importance for agency rather than ownership, despite the unexpected finding for the latter.

Despite the partly unexpected results for awareness and need for planning tasks in advance, contrasting findings emerged when perceived skill level with the prosthesis was considered. Moderate to strong positive associations between proficiency with prosthesis and all aspects of PE were found, see Figures 53-55.

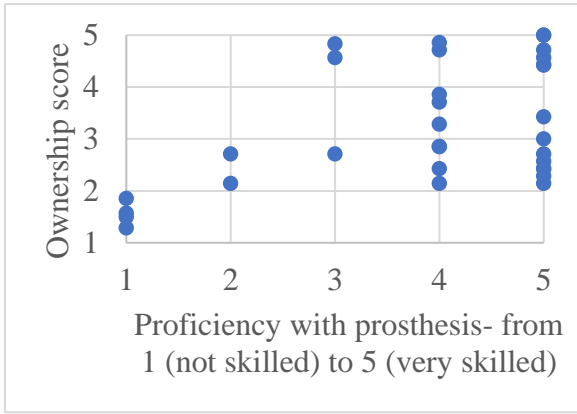


Figure 53. Positive association between proficiency with prosthesis and ownership.

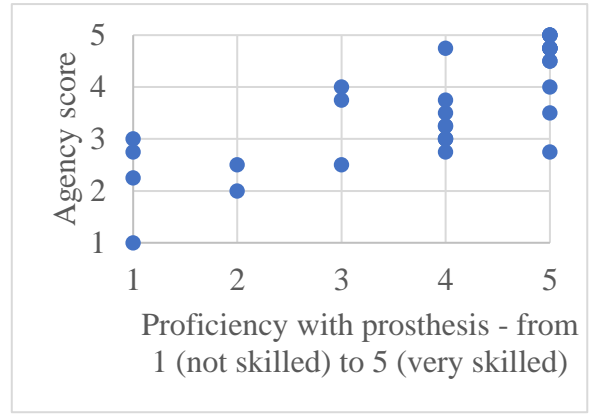


Figure 54. Positive association between proficiency with prosthesis and agency.

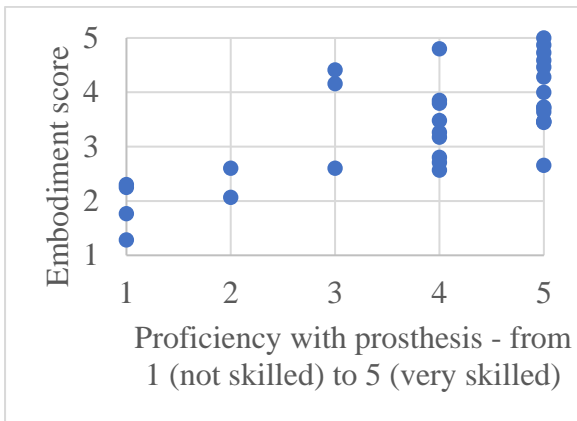


Figure 55. Positive association between proficiency with prosthesis and embodiment.

Perceived level of skill in using a prosthesis could naturally encourage PE due to feeling of control over the prosthesis resulting in more naturally perceived movement. This will likely strengthen the connection to the prosthesis, as reported by some users in the qualitative study.

**4.2.5.8 Satisfaction with prosthesis.** A group of factors centred on the level of satisfaction a user had with their prosthesis in a variety of aspects. These were identified as relevant in the qualitative study and were thus explored here in terms of their relationship with PE. See Table 21 for a list of these and the statistical findings.

Table 21

*Statistical relationships between satisfaction with prosthesis and PE*

Satisfaction with	Ownership		Agency		Embodiment	
	$r_s$	$p$	$r_s$	$p$	$r_s$	$p$
Functionality	.302	<b>.044</b>	.668	< <b>.001</b>	.547	< <b>.001</b>
Appearance	-.018	.461	.245	.085	.100	.291
Fitting	.411	<b>.009</b>	.667	< <b>.001</b>	.599	< <b>.001</b>
Comfort/weight	.221	.109	.635	< <b>.001</b>	.477	<b>.003</b>
Reliability	.170	.172	.440	<b>.005</b>	.335	<b>.029</b>
Response speed	.109	.276	.662	< <b>.001</b>	.399	<b>.012</b>
Noise	-.345	<b>.025</b>	-.011	.475	-.191	.144
Robustness	.001	.499	.199	.134	.092	.306
Prosthesis overall	.494	<b>.002</b>	.649	< <b>.001</b>	.659	< <b>.001</b>

Note: Bold = test significant at  $p < .05$ .

As shown in the Table 21, PE was found to be related to some aspects of satisfaction but not others, and sometimes with only some types of PE. *Satisfaction with functionality* was related to all embodiment measures with strong relationships, as shown in Figures 56-58.

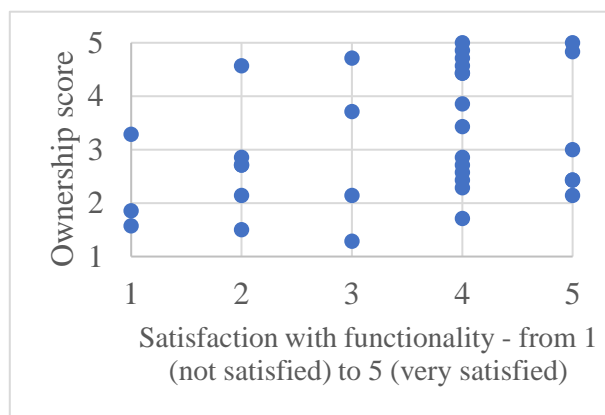


Figure 56. Positive association between satisfaction with functionality and ownership.



Figure 57. Positive association between satisfaction with functionality and agency.

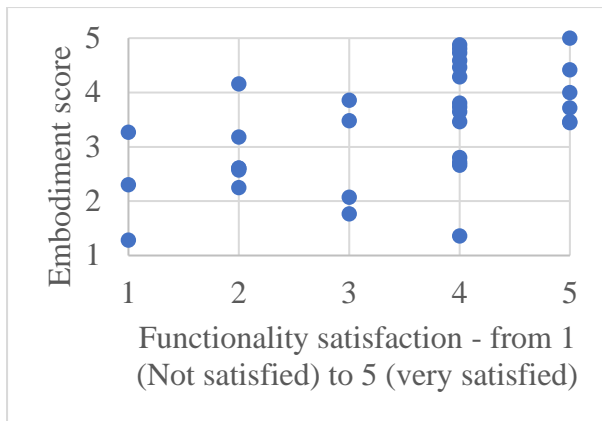


Figure 58. Positive association between satisfaction with functionality and embodiment.

A user’s satisfaction with functionality could be relevant for both ownership and agency, due to both the feeling of the prosthesis providing functions matching what the user wants from their limb, and feeling in control of the prosthesis. This might explain the relationship found with both factors of embodiment. In contrast, to experiencing satisfaction with functionality and the subsequent potential encouragement of ownership and agency, is the poor degree of functional restoration usually achievable in upper-limb prostheses (Baumgartner, 2001). There being sufficient function provided by the prosthesis has been noted as a reason for prosthetic acceptance, i.e., some use of the prosthesis (Millstein et al., 1986; Murray, 2004), and insufficient function linked to rejection (Østlie et al., 2012). This suggests that, via satisfaction of functionality, experiencing PE or not may be intertwined with acceptance or rejection of the prosthesis, respectively.

Unlike functionality, there were no relationships between *satisfaction with appearance* and any aspects of PE, which was unexpected due to importance raised in the qualitative study. In addition, cosmetic value or naturalness of appearance has been raised as a relevant factor in acceptance of a prosthesis (Millstein et al., 1986; Murray, 2004), whilst upper-limb prostheses tend to provide a poor cosmetic restoration of the limb (Baumgartner, 2001). This potentially suggests that, despite the importance of cosmesis for acceptance, the influence of appearance on PE is only relevant for some users. However, *satisfaction with fitting* was related to all aspects of PE with moderate to strong relationships, see Figures 59-61.

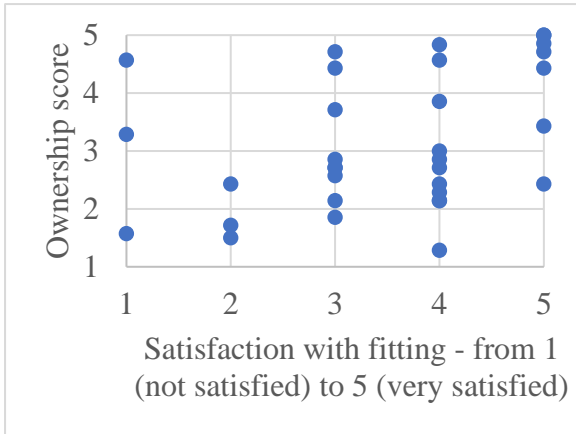


Figure 59. Positive association between satisfaction with fitting and ownership.

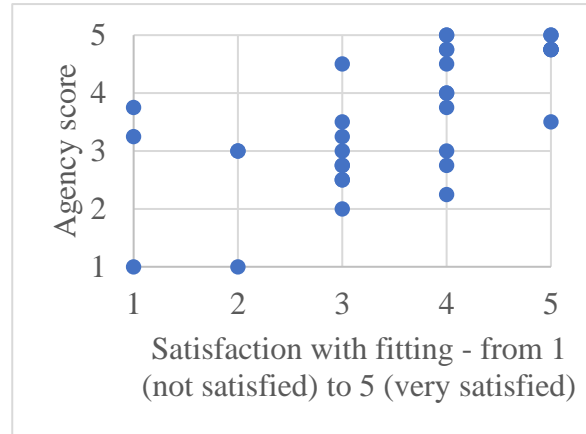


Figure 60. Positive association between satisfaction with fitting and agency.

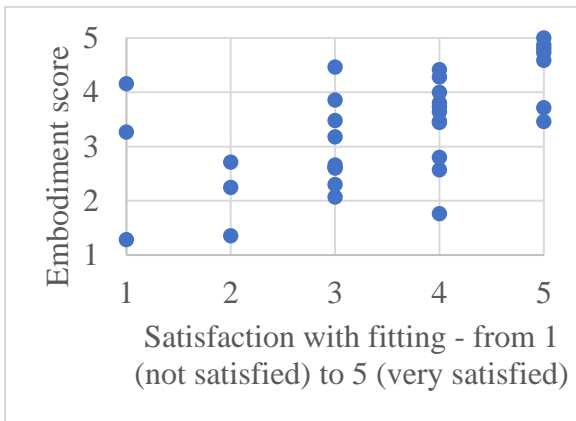


Figure 61. Positive association between satisfaction with fitting and embodiment.

Being satisfied with the fitting of a prosthesis might be important for PE in terms of the user feeling a close physical connection with their prosthesis, as a poor fit of the socket or prosthetic interface may result in a poor bond between user and prosthesis, thus impacting PE. However, it is also important for its interactions with other factors – *satisfaction with comfort/weight* and *satisfaction with reliability*. See Figures 62-63 for strong relationships between the former with both agency and embodiment.

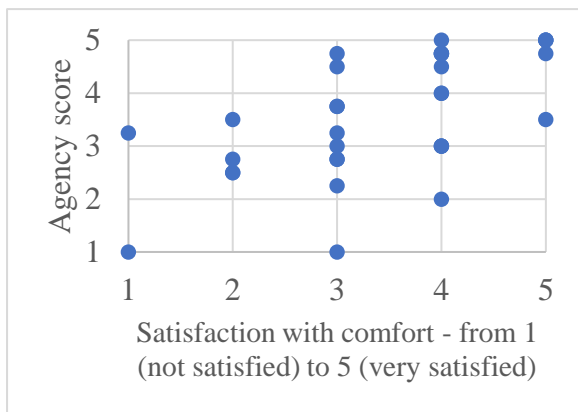


Figure 62. Positive association between satisfaction with comfort/weight and agency.



Figure 63. Positive association between satisfaction with comfort/weight and embodiment.

The prosthesis feeling comfortable is suggestibly important for feeling in control of the prosthesis and overall embodiment, but not whether there is a feeling of ownership. Comfort can also potentially impact use of the prosthesis, as sufficient comfort has been noted as necessary for prosthetic acceptance (Millstein et al., 1986), and a lack of comfort (Østlie et al., 2012) noted as a reason for complete rejection (Biddiss & Chau, 2007a). How comfortable the prosthesis feels is likely partly influenced by how well the prosthesis is fitted. Similarly, this can influence how reliably the prosthesis functions. See Figures 64-65 for the moderate relationships between the latter and both agency and embodiment.

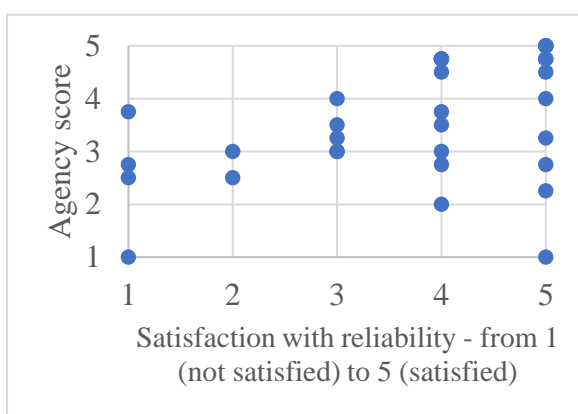


Figure 64. Positive association between satisfaction with reliability and agency.

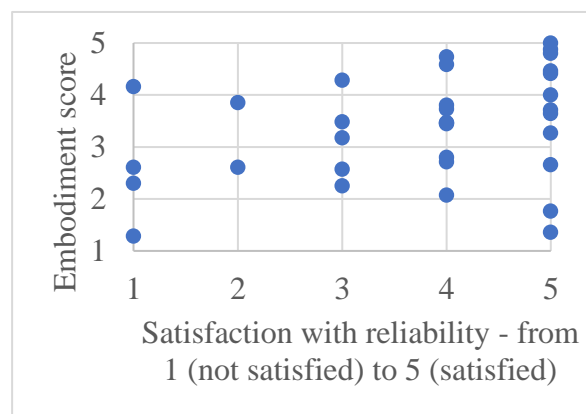


Figure 65. Positive association between satisfaction with reliability and embodiment.

Reliability of a prosthesis can be important for PE because if it is reliable, the user can depend on the prosthesis to function as if part of their body. This would heighten the sense of

agency. However, if the prosthesis became unreliable (e.g., with electrodes in a myoelectric prosthesis not functioning correctly) this could disrupt the feeling of embodiment. The relationship between satisfaction with fitting and reliability can be emphasised here, as a poor fitting has been highlighted as an influence on the functioning of myoelectric prostheses (Head, 2014). In addition, difficulty in controlling the prosthesis (Østlie et al., 2012) has been noted as a reason for complete rejection (Biddiss & Chau, 2007a). Myoelectric prostheses include a fixed delay and variability in response, introducing uncertainty over hand behaviour (Chadwell et al., 2016). Predicted response of the prosthesis based on intended movement (feed-forward model) is important for functionality (Saunders & Vijayakumar, 2011), with such feed-forward models also being important for the feeling of agency and body ownership (Kalckert & Ehrsson, 2012). These studies highlight the relevance of reliability for both rejection and PE. A related aspect here, also potentially important for PE, is response speed for functional prostheses. As expected, satisfaction with response speed had a strong relationship with agency, and moderate relationship with embodiment see Figures 66-67.

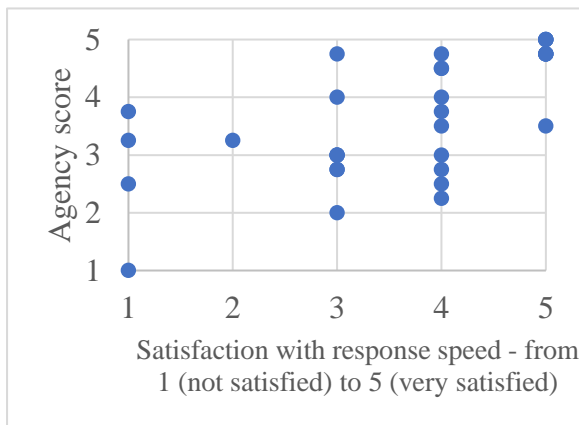


Figure 66. Positive association between satisfaction with response speed and agency.



Figure 67. Positive association between satisfaction with response speed and embodiment.

Whilst both the perception of response speed and the relative impact of this on aspects of embodiment could differ between users, this finding suggests the specific importance of response speed for agency, and to a lesser extent for overall embodiment. How quickly a functional prosthesis responds to an intended action will contribute towards how strongly the user feels like they are the agent of such action. This relates to the above discussed impact of feed forward models and, in particular, the fixed delay present in myoelectric prostheses (Chadwell et al., 2016). It is also highlighted in the moving RHI, where If the command



movement (e.g., participant's hand) and response movement (e.g., rubber hand) are synchronised this can lead to ownership and agency over the rubber hand, whereas if they are asynchronous this can disrupt embodiment (e.g., Kalckert & Ehrsson, 2012).

There was no significant relationship found between *satisfaction with robustness* and PE, suggesting this aspect may not be particularly relevant for PE, or only relevant for some users. This factor, however, might be relevant for acceptance of a prosthesis, as the prosthesis needing limited maintenance (i.e., looking after or repairing it) has been noted as a reason for accepting a prosthesis (Murray, 2004). However, satisfaction with noise had a strong relationship with ownership. See Figure 68 for this relationship.

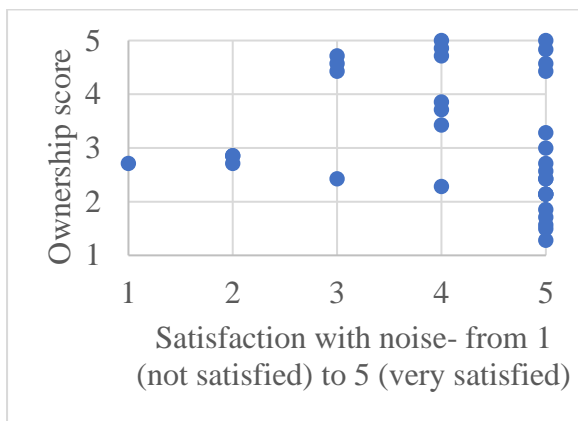
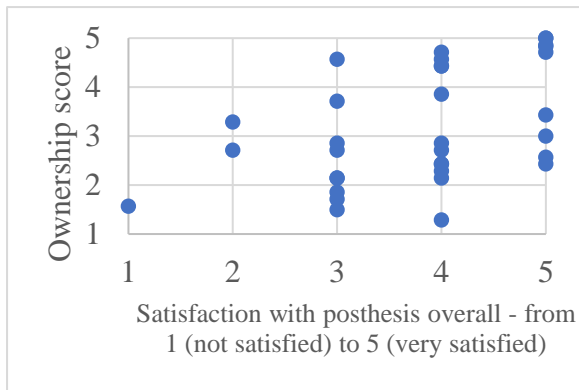
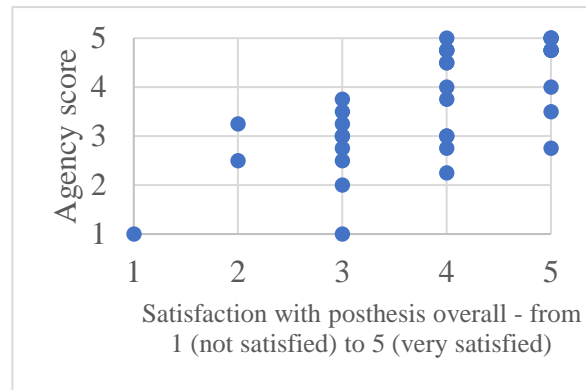


Figure 68. Positive association between satisfaction with noise and ownership.

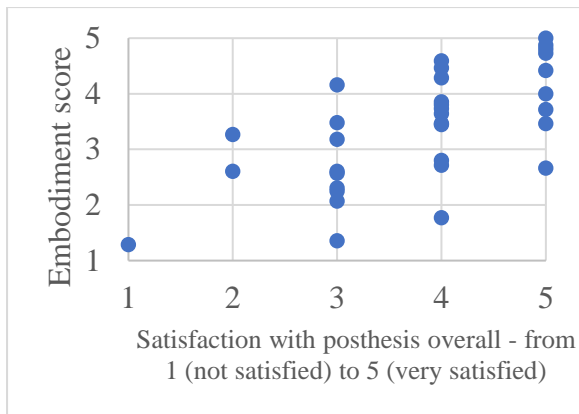
When taking into account all the above-mentioned aspects or considering how happy users were with their prosthesis in general (*satisfaction with their prosthesis overall*), there were strong positive relationships with all aspects of PE - see Figures 69-71.



*Figure 69.* Positive association between satisfaction with prosthesis overall and ownership.



*Figure 70.* Positive association between satisfaction with prosthesis overall and agency.



*Figure 71.* Positive association between satisfaction with prosthesis overall and embodiment.

Strong positive relationships between satisfaction with prosthesis and all aspects of PE highlight the importance of the former for the latter. A study by Davidson (2002) found only 24% of users reported overall satisfaction with their prosthesis. Despite this, prosthesis users will each have variable circumstances including an individual difference in expectations towards their prosthesis which will influence their overall satisfaction. Prosthesis satisfaction has also been found to be related to prosthesis use (Bilodeau et al., 2000; Davidson, 2002), and the degree to which the user is realistic in their expectations of the prosthesis may also affect prosthesis acceptance (Murray, 2004). However, the direction of the relationship between satisfaction and use is unclear. Regarding the relationship with PE, the question also remains whether greater satisfaction encourages PE, or stronger PE leads to a greater

satisfaction with the prosthesis, as both were identified as potential factors in the qualitative study.

In summary, a large range of factors were identified from the survey findings as being potentially important for one or all aspects of PE. These findings included factors focusing on use and time with the prosthesis, specific feelings, controlling the prosthesis, and satisfaction with numerous aspects of the prosthesis. Many patterns emerged, some of which were expected but with some discrepancies from the findings from the qualitative study. An overall synthesis of these results will be presented in the following section.

### **4.3 Discussion**

This survey study set out to further explore factors which were identified as potentially relevant from the qualitative study for PE. A large number of these were confirmed to have relevance in the current study, either as a statistical difference in PE within a category, or as a statistical correlation between the category and level of PE. The categorical variables were type of limb absence, type of prosthesis, phantom limb sensations, PLP, and phantom limb position, customisation of appearance. Out of these, only type of prosthesis and PLP were significantly different in PE. Discussing these first, for type of prosthesis, cosmetic prostheses were found to have the weakest embodiment, and myoelectric the strongest. These differences were considered meaningful in terms of the added functionality provided by a body-powered or myoelectric prosthesis compared to a cosmetic prosthesis, with no difference between the two functional prosthesis types.

PLP might be expected to disrupt PE from developing with the pain localised in roughly the same area as the prosthesis. However, it was expected that experiencing a phantom limb in roughly the equivalent location as the prosthesis would result in a greater encouragement of PE, but no significant effect was found. This appears to challenge previous research (e.g., Murray, 2004) which considered the importance of the correspondence of phantom and prosthetic for PE. However, the impact of a phantom limb spatially coinciding with the prosthesis might depend more on whether PLP is experienced. In addition, whilst no significant differences were found, all embodiment scores were higher when the phantom corresponded with the prosthesis, suggesting that at least for some prosthesis users this might

help encourage PE. It was also noted that the two comparison groups were small, explaining why the effect was not identified in the current study.

The lack of difference between amputees and congenitals with PE suggests that overall each group is just as likely to experience PE. Whilst some congenitals reported in the qualitative study that not having a complete anatomical arm from birth, which the prosthesis was trying to replace, encouraged PE for them, this might simply be an individual difference. Indeed, other congenitals may find it difficult to embody a prosthesis when they have not been born with that part of their limb intact. Similarly, the impact of personally customising a prosthesis may only have particular relevance for some individuals (e.g., in terms of representing their identity), hence not finding an overall significant effect here.

Some associations were found relating to aspects of time and use of the prosthesis. When associations with PE were explored these were grouped into types of factors. Whilst age of first use seemingly had no effect on PE, amount of use overall was positively associated with PE. Despite this finding, causality is unclear and 2 interpretations have been proposed to account for this finding. Unexpectedly, length of time with prosthesis and feelings changing gradually over time had no relationship with PE. However, these were reported to a lesser extent in the qualitative study and in comparison, temporary changes in PE were more strongly emphasised. This means overall feelings were more likely to fluctuate than develop gradually. Exploring the relationship between this fluctuation and PE, this survey study found a marginally significant relationship suggesting that some prosthesis users with stronger PE may be more likely to experience temporary changes to their embodiment.

Interestingly PE was found to be associated with a desire for embodiment which might suggest another factor in whether embodiment emerges for a particular user. Specific feelings suggestibly acting as a proxy for PE were found to be related to PE supporting this notion. Such feelings were feeling an emotional connection to their prosthesis, their prosthesis feeling indispensable, and feeling natural or not foreign. However, one predicted feeling which was not supported was the relationship to feeling the prosthesis as similar to glasses or other object worn on the body. The various ways in which people describe feeling towards such bodily worn objects was considered as a reason for this finding.

The positive relationship found between body image and PE potentially supported both the expectations of the qualitative study of this as an influence (i.e., body image feelings leads to PE), and an outcome (i.e., PE leads to body image changes). As with other variables which might have this dual-relationship, an experimental design would be needed to determine causality and further identify the exact relationship. determine causality. For example, by using a technique to induce PE, body image could be measured to explore potential improvements. Unlike body, the expected relationship between PE and amount of perceived negative attention was not found here, however, having a positive mindset did appear to be associated with stronger embodiment. Whilst the former might suggest this factor is only relevant for some, the latter more salient relationship could reflect an important influence. The potential implication is having a positive mindset could help encourage a user to persevere with their prosthesis, adapting to its limitations and ultimately develop PE. This was found in Murray's (2004) study where perseverance lead to initial uncomfortable or difficult experiences being negated, with more natural use and satisfaction with the prosthesis unfolding.

Aspects relating to control of a prosthesis were found to be related to PE, with type of control method, amount of benefits the prosthesis provides, amount of sensory feedback, proficiency with prosthesis. However, 2 predicted factors had no relationship with PE – awareness of prosthesis and need for planning tasks in advance. Perceived naturalness of control method influencing PE implies that users of different types of prostheses could have varying experiences of embodiment. For example, in the qualitative study a participant who had undergone TMR felt their intuitive control of their myoelectric prosthesis afforded it to feel part of them. Whereas another participant with a normal myoelectric prosthesis noted the method of flexing their muscles for EMG control to be a reason for their prosthesis not feeling part of them. With control method of a prosthesis being such a significant factor, it would be beneficial to explore the impact of this in an experimental paradigm. This would also be useful due to causality being unable to determine with correlational data, and with potential alternative interpretations of results being proposed.

Greater sensory feedback being associated with PE supports previous research (e.g., Wijk & Carlsson, 2015) and current strand of research developing prosthetics with sensory feedback to induce PE (e.g., Rognini et al., 2018). In addition, the relationship found between proficiency with prosthesis and PE supports the finding in the qualitative study, but this acted

as both an influence and an outcome of PE. Similarly, here the relationship found could mean either of those connections. If stronger PE encourage proficiency, this supports suggestions that PE will lead to functional improvements (Wijk & Carlsson, 2015) or increased intuitive control of the prosthesis (Makin et al., 2017). It is unclear why awareness of prosthesis and need for planning tasks found no positive relationship with PE. In the qualitative study both of these were identified as potential influences and outcomes of embodiment. For awareness, the lack of relationship suggests that awareness of the prosthesis could vary for both with those with and without stronger PE. In addition, those experiencing PE could still need to plan specific tasks just as much as those with limited PE.

Satisfaction with aspects of a prosthesis were found to be significantly related to PE. These aspects supported findings from the qualitative study, including functionality, fitting, comfort, reliability, response speed, and overall prosthesis satisfaction. However, satisfaction with appearance, robustness, and noise were not related to PE. The latter two were speculated to only affect some individuals, hence the non-significant association, whereas satisfaction with appearance would be expected to be salient to more prosthesis users. Perhaps this reveals that whilst the cosmetic properties of a prosthesis can be important to a user, this does not necessarily relate to PE for some. For example, someone with low embodiment could still be satisfied with their prosthetic appearance. In general, the factors which appear relevant for potentially encouraging PE centre on being satisfied with having a comfortable fitting and being satisfied with how well the prosthesis functions. An important implication is that each individual will have their own threshold for satisfaction, thus an objective level of functionality or comfort may be difficult to determine.

The current study was limited in terms of the sample size achieved. As referred to in the recruitment strategy, a large number of sources were identified but with a relatively small response rate. The target population of upper-limb prosthesis users are notably more difficult to recruit than lower-limb users due to the much smaller prevalence. It is possible some of the relationships explored with smaller groups were not large enough to gain an accurate view of significant differences or relationships. In addition, not all factors identified during the qualitative study were included for practical purposes, for example it was measured whether someone's feelings had changed temporarily but not the exact reason why. It was decided to focus on the broader factors associated with embodiment as these could be more clearly identified, instead of idiosyncratic influences on embodiment for each individual. However, a

more central limitation, as raised numerous times, is the inability to determine causality from the correlational data, making some interpretation of relationships challenging.

In conclusion, the study has potentially confirmed a number of factors related to PE, some of which were previously identified as influences on whether some experiences PE. However, some identified were those which could be either influences or outcomes. On this note, it is recommended that an experimental approach is taken to explore such highlighted factors individually and determine the true nature of their relationship to PE. One such variable mentioned is control method of the prosthesis, as this is likely be an important aspect of experiencing an upper-limb prosthesis and identified here as a potential influence of PE. An Immersive Virtual Reality system could provide a useful tool to explore the impact of factors on PE in a controlled systematic way.

## Chapter 5: VR experimental study

This chapter will recap on findings from the prosthetics literature regarding control of myoelectric prostheses, the use of IVR simulations to test factors influencing PE, the use of body ownership techniques for exploring PE, and implications from research findings utilising such techniques relevant for PE. It will detail the main and additional aims of the study, the method used, along with mention of additional preparation work. Quantitative and qualitative findings will be presented along with a discussion of the implications for PE and further studies.

### 5.1 Background

As identified in the literature review chapter, the difficulty in controlling myoelectric prostheses has been widely reported (e.g., Biddiss & Chau, 2007a; Chadwell et al., 2016) and can lead to rejection of the prosthesis (Biddiss & Chau, 2007b). One reason for this may be because myoelectric prostheses include a fixed delay and variability in response, introducing uncertainty over hand behaviour (Chadwell et al., 2016). Saunders and Vijayakumar (2011) also highlighted the importance of predicted response of the prosthesis based on intended movement (*feed-forward model*) for functionality.

Such feed-forward models have also been identified as being important for the feeling of agency and body ownership (Kalckert & Ehrsson, 2012), with voluntary movements producing an efferent copy that produces an expected sensory outcome. This is highlighted by a version of the rubber-hand illusion (RHI), in which a participant moves their hand and sees a rubber hand move. If the command movement (participant's own hand) and response movement (rubber hand) are synchronised this can lead to ownership and agency over the rubber hand (e.g., Kalckert & Ehrsson, 2012). Similar studies have replicated this finding using virtual hands (e.g., Sanchez-Vives et al., 2010; Yuan & Steed, 2010), and when movement is asynchronous this can disrupt embodiment. Thus, the timing of intended movement with actual movement may be one of the factors influencing whether or not PE occurs for functional prostheses.

A broader potential influence on PE to consider first for functional prostheses, is the control method of the prosthesis, with muscles flexes used to initiate hand movements for



myoelectric prostheses. Referring to findings from body ownership literature, research has shown the RHI, despite being less vivid, is still possible with modality-mismatched feedback, for example, replacing touch with vibration (D'Alonzo & Cipriani, 2012; D'Alonzo et al., 2015). Whilst this utilised the traditional visuo-tactile stimulation RHI (e.g., feeling and seeing paintbrush strokes on hands), it is anticipated an equivalent effect may occur with visuo-motor stimulation, for example, with a prosthetic hand being controlled with muscles flexes. Despite this expectation, it might also be expected that sense of ownership would be significantly reduced when controlling a prosthesis compared to natural control of an anatomical hand. This is because of the sensory substitution in addition to the missing sensory information that would be available with natural hand control. Notably, when there are multiple matching sensory signals arising from a limb this leads to the sense of ownership over the limb (Kalckert & Ehrsson, 2012). In addition, reduced agency could be expected, as the efferent copy is compared with actual feedback to determine whether sensations are internally generated (Kalckert & Ehrsson, 2012).

However, it is currently unknown what impact the control method (i.e., controlling movement with muscles flexes compared to natural hand movement) has on embodiment. Thus, the question remains whether PE in myoelectric prostheses is naturally hindered (aside from other potential additional constraints e.g., unreliability, appearance, and comfort) from the person having to learn to control the prosthesis via flexing their muscles. In addition to the unnatural control input for hand movement, is the reduced control over the prosthetic hand compared to an anatomical hand. This is highlighted by a user in Saradjian et al.'s (2008) study, who noted that whilst they could open and close the fingers (as one) and thumb of their myoelectric prosthesis, this capability is far from the full dexterity of an anatomical hand. The reduced control might suggest that the feeling of agency could be reduced compared to full control of a hand. Further to this, the difficulty in control of a myoelectric prosthesis and potential unwanted activations of the hand could reduce the sense of agency.

Christ and Reiner (2014) highlight possible applications of a RHI combined with VR for rehabilitation. One approach of applying the use of body ownership techniques to prosthetics in VR involves exploration of factors that naturally influence PE using a VR prosthesis simulation. VR simulations have been previously used to aid optimisation and development of prostheses (e.g., Hauschild, Davoodi, & Loeb, 2007; Lambrecht, Pulliam, & Kirsch, 2011; Resnik et al., 2011). Similarly, such simulations could be utilised to

experimentally explore the impact of specific factors on PE. As highlighted in the literature review, steps towards this have begun but the focus has been on exploring other aspects associated with prosthesis use, such as phantom limb pain. Mirroring this, in the body ownership literature in general, agency over a rubber or virtual hand has been explored. This could have relevance for embodiment of functional prostheses but has not been specifically focused on embodiment of prosthetics or systematically measuring the impact of the control method of a virtual prosthesis.

An IVR study was proposed to systematically measure the impact of control method, with the consequent aim being to understand how such a factor might influence embodiment of myoelectric prostheses. IVR is particularly useful to explore the research questions as it offers the ability to manipulate the visual world as it appears to participants, specifically to control variable factors (Kiltner et al, 2012). The study involved altering the control method of the prosthesis whilst keeping the visual presentation of the prosthetic arm movement constant, thus considering the impact of using muscles flexes, instead of natural hand movements, on embodiment.

The study also explored the relationships between specific factors or PE to further develop understanding of PE. Such relationships included exploring the relationship between ownership and agency to see if these aspects of embodiment influence each other (e.g., a greater feeling of agency potentially encouraging a feeling of ownership). Also, exploring the relationship between ownership and physiological response to a threat applied to the virtual prosthesis. If such a relationship exists it might suggest that with PE, users behave as if the prosthesis is their own arm, when it is threatened.

An additional aim of the study is to explore the suitability of the VR system for exploring PE in future studies. This consists of two aspects – one being the overall level of embodiment achievable with control of the myoelectric prosthesis, based on experimental measures; the other being the accuracy of the VR system in displaying hand movements and exploring any potential impact on findings. The former is important, not just for informing the current study, but also for future studies as if specific delays wish to be introduced (to explore the impact on certain delays on PE) a certain level of embodiment may be needed without any additional delays.

To encourage the highest amount of PE possible, inherent delays from processing motion tracking of hand movement and presentation of the virtual prosthesis movement (latency) combined with delay from the prosthesis, along with accuracy of the VR system were tested prior to the study (mentioned further in the method section). In prior testing, the lowest latency and highest accuracy were sought with the equipment being used. A latency considered suitable for the experiment was achieved but accuracy was found to be more variable so during the experiment this was measured along with statistically and qualitatively measuring the impact of this on findings. This additional testing was considered important for both having confidence in findings and helping to inform the design or interpretation of future VR prosthetics studies.

Based on previous body ownership literature outlined above, a specific set of outcomes were expected. These were that all embodiment scores and skin conductance would not be as strong when controlling via EMG, ownership scores would positively correlate with both agency scores and skin conductance, and that greater accuracy issues would reduce all embodiment scores for both conditions. The IVR study research questions and associated hypotheses are:

1) What is the level of overall embodiment (questionnaire scores) achieved with the IVR setup (to help inform the follow-up IVR study)?

- H1: All subscale and embodiment scores will be significantly higher than their respective control subscale scores in both conditions
- H2: Skin conductance will be significantly higher when a knife threatens the virtual prosthesis compared to a period of time before the threat in both conditions

2) What is the relationship between ownership and agency (questionnaire scores) of a virtual prosthesis?

- H3: There will be a positive relationship between ownership and agency scores in both conditions.

3) What is the difference in embodiment (questionnaire scores) of a virtual prosthesis when this is controlled by either a participant's hand or a muscle flexes controlling a myoelectric prosthesis?

- H4: Ownership scores will be significantly lower for the EMG control (prosthetic hand condition) than natural hand control (hand condition).
- H5: Agency scores will be significantly lower for the EMG control (prosthetic hand condition) than natural hand control (hand condition).
- H6: Embodiment scores will be significantly lower for EMG control (prosthetic hand condition) than natural hand control (hand condition).

4) What is the level of skin conductance response achieved with the IVR setup (to help inform the follow-up IVR study)?

- H7: Skin conductance will be significantly higher when a knife threatens the virtual prosthesis compared to a period of time before the threat in both conditions

5) What is the relationship between ownership and/ physiological response (measured by skin conductance and behavioural reaction) to a virtual threat?

- H8: There will be a positive relationship between ownership and skin conductance scores in both conditions.

6) What is the difference in skin conductance response scores when the virtual prosthesis is controlled by either a participant's hand or a muscle flexes controlling a myoelectric prosthesis?

- H9: Skin conductance scores will be significantly lower for the EMG control (prosthetic hand condition) than natural hand control (hand condition).

7) How accurate is the movement of the virtual prosthesis and what impact does it have on the findings?

- H10: There will be a negative relationship between inaccuracy (amount of accuracy issues) and all embodiment scores and skin conductance in both conditions.
- H11: Those who have greater accuracy issues will have significantly lower embodiment scores and skin conductance in both conditions.

## 5.2. Method

**5.2.1 Design.** A repeated measures design was employed with the independent variable of virtual hand control method, with two conditions 'prosthesis' and 'anatomical

hand'. In the anatomical hand condition participants used their own hand and, in the EMG control condition the prosthetic hand was used. For both conditions one virtual prosthesis appearance will be used. Dependent measures include scores on a virtual hand ownership and agency questionnaire adapted from Kalckert and Ehrsson (2012), including separate scores for 'ownership', 'ownership control', 'agency', 'agency control', 'embodiment', and 'embodiment control'. A further dependent measure is skin conductance response from a threat applied to the virtual hand. Physical behaviour of a participant's actual right arm/hand at the moment the threat also acted as an additional dependent variable, measured by coding from videos whether this was moved as the moment of the knife animation. In addition, qualitative responses were collected and analysed from questionnaires and in response to post-experiment questions.

**5.2.2 Participants.** To decide on a minimum sample size to aim for, other embodiment studies using similar techniques and design were reviewed. This suggested that a sample size of 30 should be sought. The sample consisted of 31 anatomically-intact students and staff who were recruited from the University of Salford via poster advertisements and through undergraduate seminars. The sample consisted of 17 Males (Mean age = 30) and 14 Females (Mean age = 35). For males, 16 were right-handed, with one left-handed participant. For females, 12 were right-handed, with two left-handed participants.

**5.2.3 Materials.** A *Steeper* select threshold controlled myoelectric prosthetic hand which opens and closes via EMG signals from electrodes measuring arm muscle flexes was used (see Figure 72).



*Figure 72.* Myoelectric prosthetic hand.

For use in both developing the virtual demo, and displaying the virtual environment to participants via first-person perspective tracking, an *Oculus Rift* (DK2) IVR head-mounted display (HMD, see Figure 73) was used. This displayed the virtual demo which was developed on *Unity*, *Make Human*, and *Blender* software.



*Figure 73.* Oculus Rift HMD.

In order for hand for hand movement tracking and displaying the equivalent virtual arm movement, *Leap Motion* device and software were used. See Figure 74 for an image of the device and a representation of the traditional set up when used outside of IVR displaying just on a monitor/laptop screen.



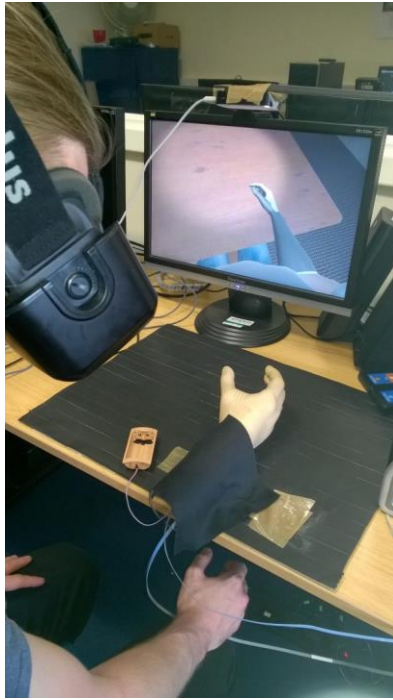
*Figure 74.* Leap Motion device and example virtual hands.

As will be detailed in the prior testing section further down, multiple Leap Motion rigs were developed and testing with the device pointing downwards at the hand so would be suitable for use with the prosthetic hand. This was based on a setup used by Argelaguet et al. (2016), see Figure 75 for an image of this.



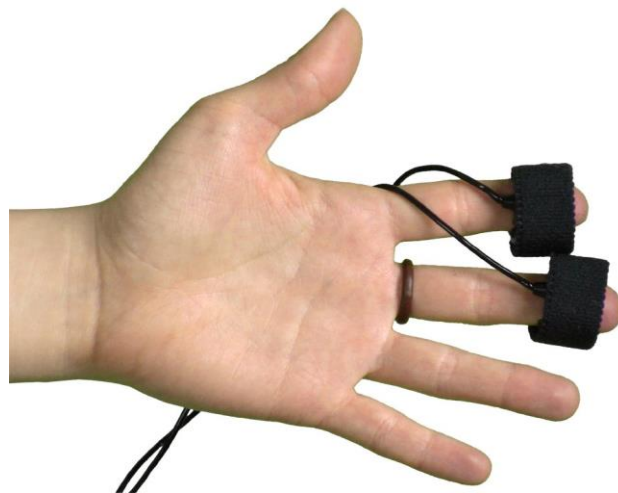
*Figure 75.* Example of experimental setup with Leap Motion fixed to shelf (taken from Argelaguet et al., 2016).

See Figure 76 for the experimental setup developed for this study. This included the Leap Motion secured to a frame resting over the location of the prosthetic hand. In the ‘prosthesis’ condition (displayed here), the prosthetic limb is controlled from arm movements resting below the desk. In the ‘hand’ condition the participant’s anatomical hand rested on the desk in place of the prosthesis. The PC monitor behind displays the participant’s viewpoint of the vestural avatar.



*Figure 76.* Experimental setup.

Skin conductance (skin electrical activity) was measured during the experiment and in response to a virtual threat (an animation of a knife dropping onto the table in between the fingers and thumb of the virtual prosthesis). Skin conductance was measured from the left hand, which remained still, as the right hand was controlling the virtual prosthesis. See Figures 77 and 78 for the *Biopac MP36* skin conductance system, which measured skin conductance in microsiemens repeatedly at 200 samples a second over specific time periods.



*Figure 77.* Electrodes from Biopac MP36 system attached to left hand.





*Figure 78.* Biopac MP36 system.

In addition to skin conductance hardware, *Biopac Student Lab Pro* and *AcqKnowledge* software were used to collect and analyse skin conductance data. To find the optimal location for placement of electrodes of the myoelectric prosthetic hand (in order to encourage the amplitude of the signal in controlling the prosthetic hand) a *MyoBoy* device (see Figure 79) was used during the experiment along with *PAULA 1.2.* software from prosthetics company *Ottobock*.



*Figure 79.* MyoBoy (taken from <https://professionals.ottobockus.com/>)

Further equipment included an *MSI GS30 2M Shadow* laptop with base station to run the Unity VR demo. The laptop includes an *Nvidia GeForce GTX 980* graphics card and the CPU is an *Intel Core I7*. The demo was displayed on a separate standard PC monitor (*ProLite*

B1902S, refresh rate 60Hz) as while the demo can be seen by participants via the Oculus Rift, the laptop is unable to display this on the screen. In addition, a *Panasonic Lumix DMC-FZ200* camera and tripod which was used to film participant's behaviour during presentation of a virtual threat to the virtual prosthesis, along with filming the PC monitor showing the virtual environment to later assess accuracy.

See Appendix O for ethical approval letter. A participant recruitment email was created along with a study poster (See Appendix P). See Appendix Q for the PIS, Consent Form, and Debrief Sheet. In addition, a background information form (See Appendix R) collected information from participants during the study – age, gender, hand dominance, and previous experience with Virtual Reality and control of a myoelectric prosthesis. For assessing embodiment, a virtual hand ownership and agency questionnaire was adapted from Kalckert and Ehrsson (2012) to subjectively measure embodiment (see Appendix S). The questionnaire includes questions measuring ownership, ownership control questions, agency questions, and agency control questions. Scores for each section are calculated based on the mean response from the items. Questions 1-4 represent the feeling of ownership. Questions 5-7 represent ownership control questions. Questions 8-11 represent the feeling of agency. Questions 12-14 represent agency control questions. Scores above 4 represent an overall agreement with the statements (e.g., ownership), and below 4 representing a disagreement.

At the end of the questionnaire a free-text response was completed by participants to capture their experience of the virtual prosthesis in a different way than the pre-set questions:

*Please can you freely describe how you felt towards the virtual prosthesis during the hand movements*

In addition, a short interview was conducted with participants after completion of both of the experimental conditions where additional questions were asked to capture their awareness of the accuracy of the virtual simulation and any potential impact on experience of the prosthesis, any impact from their actual hand being spatially different between conditions (on table, for anatomical hand control, under table for prosthesis control), and their feelings towards the knife being a threat to the virtual hand. The questions were:

*Q1) Were you consciously aware of the accuracy of the virtual hand (for example, whether fingers were moving correctly or in the wrong position)?*

*Q2) Did the accuracy influence your experience in terms of the questions you completed?*

*Q3) Did having your hand over or under the table influence your experience in terms of the questions you completed?*

*Q4) Did you feel the knife was a threat to the hand?*

Participants answered questions verbally with answers being written down by the experimenter.

**5.2.4 Prior testing.** In development of the VR environment to be used in experiments, and use of hand motion tracking, it was acknowledged that the latency (i.e., delay from hand movement input to virtual hand display output) and accuracy (i.e., how well the hand movement matched the virtual hand movement) of the motion tracking could impact on experience of the virtual prosthesis and experimental findings. This is important due to the relevance of each for embodiment suggested in body ownership literature. In addition, there is an inherent electromechanical delay from controlling a myoelectric prosthesis which needed to be considered. Thus, details of a review of embodiment studies, demo development, prosthetic hand delay, and latency and accuracy analysis are mentioned below.

**5.2.4.1 Summary of embodiment studies.** In order to understand whether the optimal latency of the demo being developed for the VR study would be acceptable for inducing embodiment, an in-depth review of psychological embodiment studies was considered necessary. This aimed to identify how embodiment is specifically affected by delays that are either introduced or inherent in stimulation from RHI/VHI studies. See Appendix T for the full review. The conclusion from the review was that a total delay between prosthesis hand and hand tracking) should aim to be below 300ms for a stronger RHI-effect.

**5.2.4.2 Prosthetic hand delay.** In addition to latency from the VR system there is an electromechanical delay when opening and closing a myoelectric hand. Two types of prosthetic hand were available for the study, one by the prosthetics company Steeper, the other by *Ottobock*, an Ottobock Variplus hand. Based on an investigation into delays by Dr. Alix Chadwell during her PhD (See Appendix U), the delay varied between the Steeper hand and Ottobock hand, whether the hand is opening or closing, and whether it is opening or closing fully or from a neutral position. The Steeper hand produced a fairly consistent amount of delay in both a full opening and closing of below 100ms. The Ottobock hand could achieve around 100ms delay if the hand was opening and closing from a neutral position.

These figures also match those found to match an optimal controller delay for myoelectric prostheses (Farrell & Weir, 2007).

**5.2.4.3 Leap motion latency and accuracy analysis.** An investigation into the latency and accuracy of Leap Motion was conducted, which included: 1) Exploring guidelines for optimisation, 2) Implementation of various settings and testing of both latency and accuracy of the VR system being used. See Appendix V for the full investigation. Through this process the impact of various hardware and software settings on latency and accuracy were explored to identify the specific set of circumstances which appeared to minimise latency and maximise accuracy.

**5.2.4.4 Demo development.** The demo used in the VR system for experiments had to be developed ground up as part of the PhD. See Appendix W for the full detailing of the various aspects and steps in this process. This included, learning of hardware (e.g., Oculus Rift, Leap Motion) and software (e.g., Unity, Make Human), development of a VR environment, first-person perspective of an amputee avatar, testing various Leap Motion software, developing multiple Leap Motion ‘rigs’ (i.e., where the physical device should be placed for experiments), and exploring options for appearance of the virtual hand available.

**5.2.5 Procedure.** Participants rested their arm on their leg below a table with their hand positioned below the prosthetic hand on the table. With the HMD they had a first-person perspective looking down at a virtual prosthesis. Participants observed opening and closing the virtual prosthesis hand 60 times via the EMG electrodes following a visual instruction to open or close their hand. Number of hand movements was decided based on consideration of time need for response to instruction and hand movement (1 movement every 2 seconds), along with a review of RHI/VHI experimental studies which suggested a stimulation period of 2mins to encourage embodiment. At the end, a virtual threat was applied to the virtual prosthesis with an animation of a knife dropping onto the table in between the fingers and thumb of the virtual prosthesis (See Figure 80 for an image of this).



*Figure 80.* Virtual knife threat.

Physiological measurement was taken at various times and participant behaviour was filmed during the main experiment part. After the experiment the embodiment questionnaire was completed and then the experiment repeated with participants resting their hand in the same location as where the prosthetic hand was placed, and then opened and closed their hand instead of the prosthetic hand.

### **5.2.6 Analysis.**

**5.2.6.1 Questionnaire analysis.** To test whether there is evidence for a VHI-effect, questionnaire embodiment subscale scores were compared with respective subscale control scores using Wilcoxon tests. In addition to considering main subscale scores in relation to a cut-off score of 5 or above. The relationship between ownership and agency was explored through Spearman's rho correlations. Scores were compared between conditions using t-tests and Wilcoxon tests. Order effects were also analysed using t-tests and Wilcoxon tests to check if which the order of the conditions participants completed had influenced results.

**5.2.6.2 Skin conductance analysis.** Skin conductance was collected during the whole period of the main experiments but was specifically assessed in a 2-second period when the hand was still and no threat present, and during the 10-second threat period (i.e., the time in which the virtual knife was visible and close to the virtual prosthesis). The latter was to decide the most appropriate number of seconds in which to include the highest microsiemen value. After assessment this was decided to be during the first seconds. The skin conductance response (SCR) to the threat was calculated by taking the highest value in the experimental

period during the knife drop (*Experimental highest*) minus the average value in the 2 seconds before the knife dropped (*Experimental baseline*), the skin conductance level (SCL).

**5.2.6.3 Content analyses of free-text responses and post-experiment questions.** A Content Analysis was conducted on the free-text responses provided in the questionnaire to capture experience of the virtual prosthesis in a different way than questions. Codes were developed from the data, identifying specific categories which were grouped into themes. Percentages were calculated from frequencies of each category (i.e., what percentage and how many participants mentioned the specific category) to compliment presentation of the analysis. A Content Analysis was also conducted on each of the post-experiment questions. For each type of response to a question, percentages were calculated from frequencies. In addition, codes emerging from the data identified categories as reasons for each specific response. (i.e., why they answered a particular way).

**5.2.6.4 Accuracy analysis.** The accuracy of the virtual hand compared to the anatomical or prosthetic hand was captured and analysed to assess any potential impact upon the experimental conditions (i.e., experience of the virtual prosthesis). Analysis procedure was developed from the prior accuracy testing process (during development of the VR demo), capturing specific categories of accuracy. Participant videos were analysed using *Tracker 4.96 (Open Source Physics)* software assessing virtual hand movement frame-by-frame. The virtual hand on the PC screen along with the prosthetic or participant's hand were observed for all hand movements from the first movement until the hand is still and the knife animation begins. For each participant in each condition specific categories were counted and coded in an Excel spreadsheet:

- *Virtual hand vanishes* = the virtual hand vanishes from the display.
- *Virtual hand switches* = the virtual hand is displayed as a left hand.
- *Virtual hand incorrect position* = the virtual hand is displayed in a noticeably different orientation as the prosthetic/participant hand.
- *Virtual hand in-appropriate movement* = the virtual hand movement is relevant to the movement of the prosthetic/participant hand, either opening, closing, or remaining still.
- *Incorrect virtual fingers* = the fingers/thumb display noticeably incorrect movement such as moving the incorrect direction or not moving when the hand is still.

- *Virtual fingers flickering* = the fingers/thumb flicker.

A total overall inaccuracy figure was calculated by summing the total of all instances of the above for each participant. Total figures and percentages were also calculated for individual categories across the group and for each condition.

### 5.3 Results

On the participant background information sheet previous experience with Virtual Reality and control of a myoelectric prosthesis was captured. See Table 22 for a summary of this.

Table 22

*Participants' previous experience with Virtual Reality and controlling a myoelectric prosthesis*

Amount of experience	Experience with Virtual Reality	Experience with controlling a myoelectric prosthesis
None	9	29
Some	18	2
Familiar	4	0

Table 22 shows that nearly two thirds of participants had previously had some experience VR, but only a very small number of participants were familiar with VR and nearly one third had never tried VR. Whereas, nearly all participants had never controlled a myoelectric prosthesis, with only a couple of participants having had some experience of this.

#### 5.3.1 Embodiment questionnaire.

**5.3.1.1 Questionnaire descriptive and inferential statistics.** See Figure 81 for descriptive statistics of sub-scale scores (Medians) on the questionnaire for both the prosthesis and hand conditions.

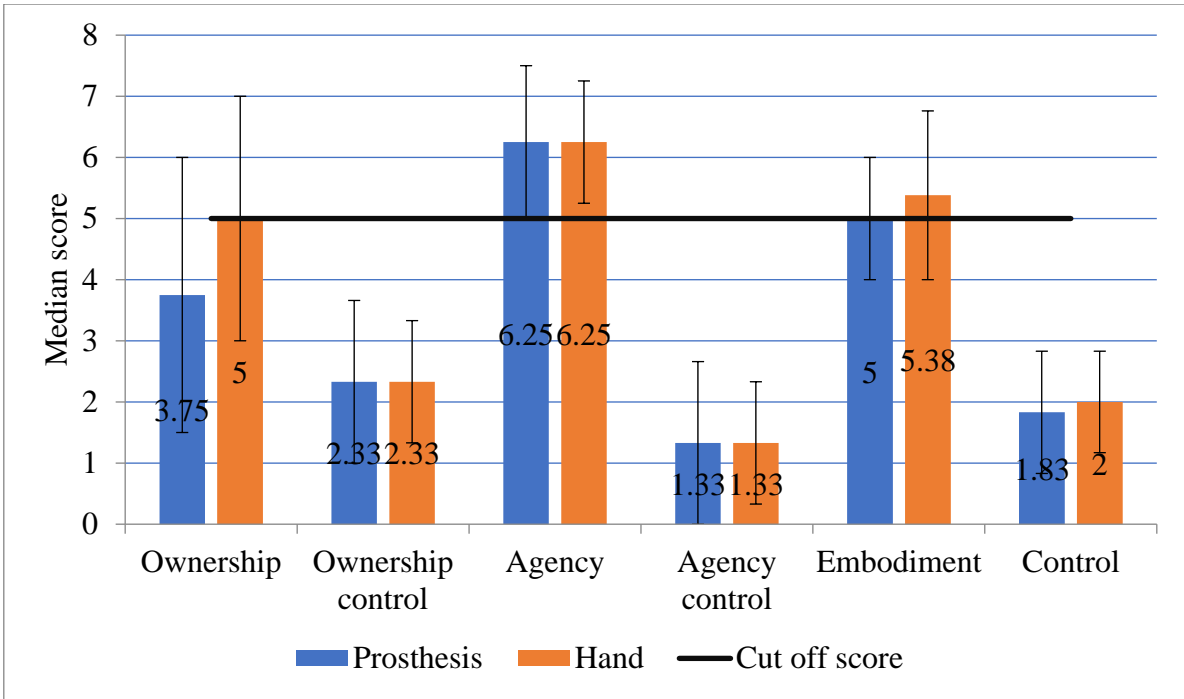


Figure 81. Median sub-scale scores for ownership, agency, embodiment, and respective control scores split per condition. with error bars representing the Interquartile Range.

The cut-off score shown in Figure 81 is based on the criteria of scores averaging to 5 or above (i.e., rounded to 5, 6, or 7) representing an overall agreement with the statements (e.g., ownership effect), and below 4 representing a disagreement. See Figures 82-93 for frequency histograms of scores for each sub-scale compared between conditions.

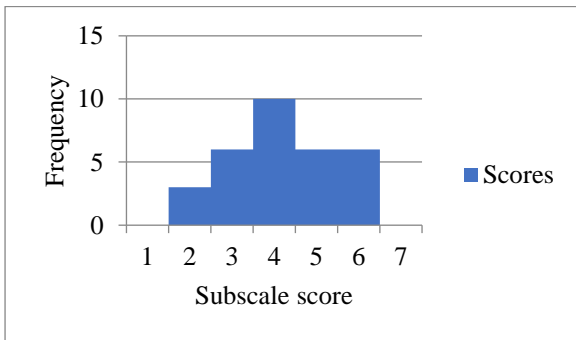


Figure 82. Scores for prosthesis ownership.

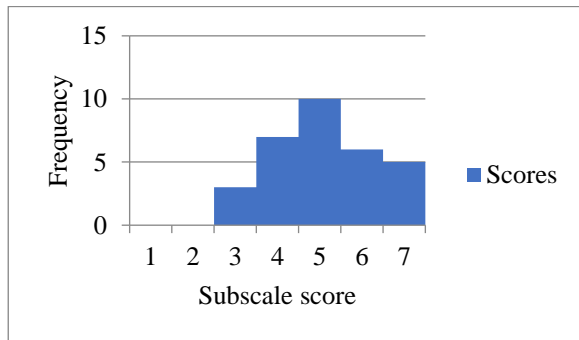


Figure 83. Scores for hand ownership.



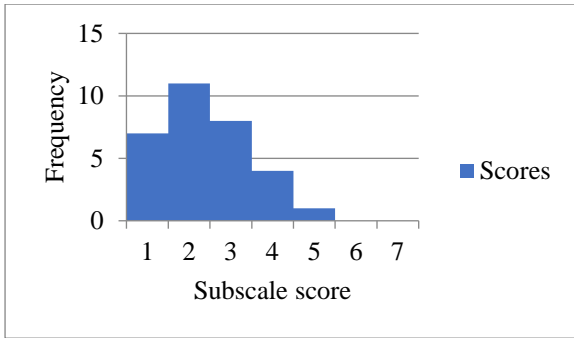


Figure 84. Scores for prosthesis ownership control.

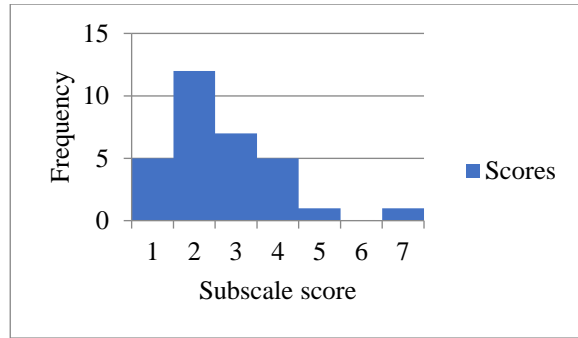


Figure 85. Scores for hand ownership control.

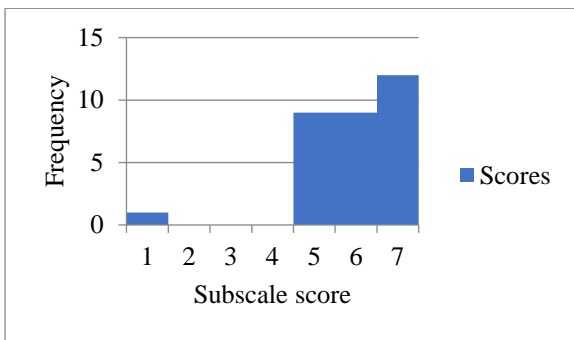


Figure 86. Scores for prosthesis agency.

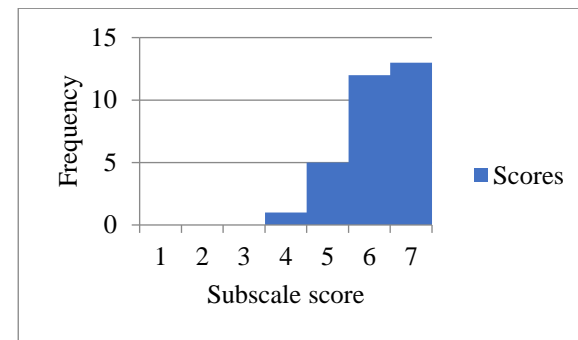


Figure 87. Scores for hand agency.

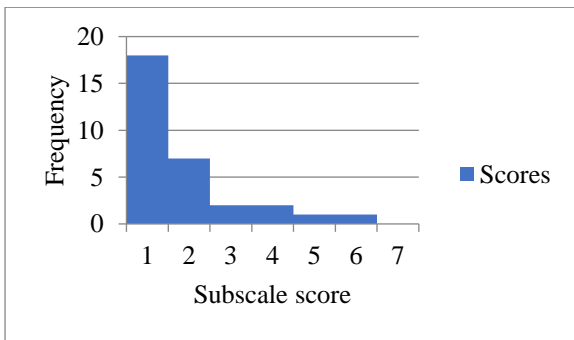


Figure 88. Scores for prosthesis agency control.

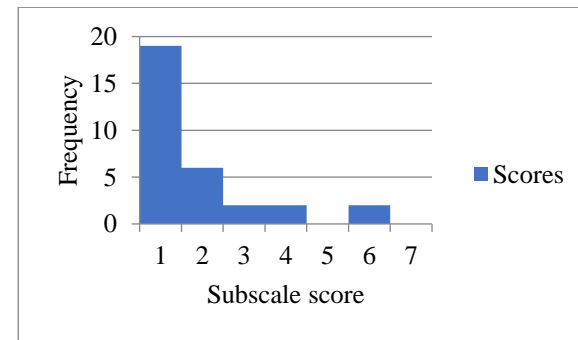


Figure 89. Scores for hand agency control.

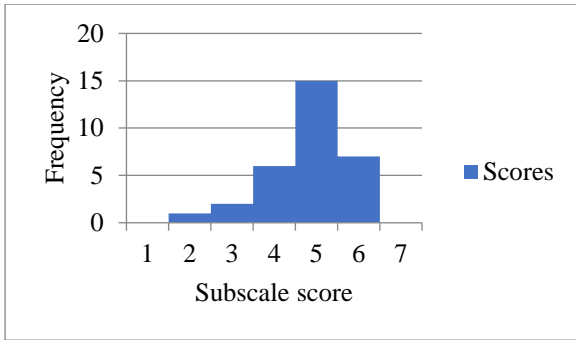


Figure 90. Scores for prosthesis embodiment.

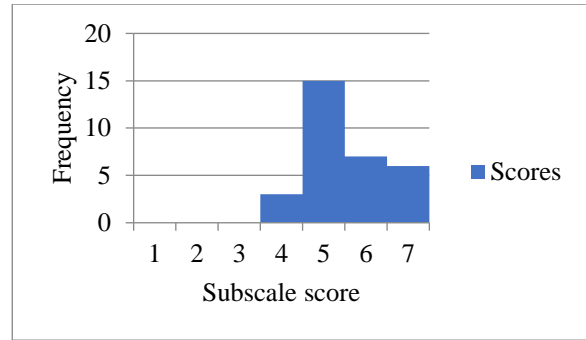


Figure 91. Scores for hand embodiment.

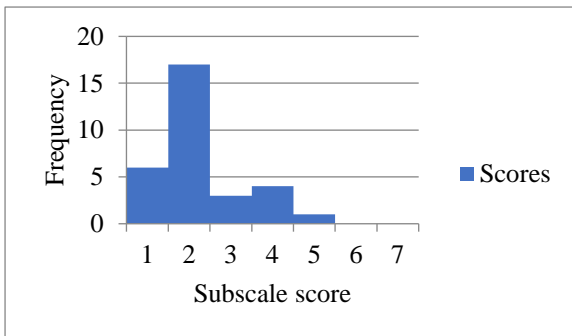


Figure 92. Scores for prosthesis embodiment control.

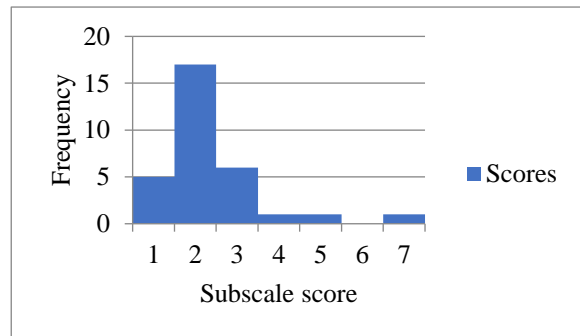


Figure 93. Scores for hand embodiment control.

For the prosthesis condition the ownership score had an overall value of 3.75 indicating ownership was not positively endorsed but also not disagreed with. Referring to individual values, 10 out of 31 participants experienced a positive (score of 5 or above) ownership score. In comparison, the ownership control questions were on average disagreed with and only 1 participant had an overall agreement with these. For agency, there was an overall agreement (1 participant showed disagreement), and agency control scores, an overall disagreement (2 participants showed agreement). All participants experienced this, and this was slightly higher than ownership. Combined embodiment scores show overall embodiment effect (9 participants showed disagreement), whereas embodiment control displays disagreement (2 participants showed agreement).

For the hand condition there was overall agreement for ownership (10 showed disagreement), whereas ownership control was disagreed with overall (2 showed agreement). Agency showed overall agreement (1 participant showed disagreement), whereas agency control was disagreed with (2 participants showed agreement). Embodiment showed overall agreement (3 participants showed disagreement), whereas embodiment control was disagreed

with (2 participants showed agreement). Ownership, agency, and overall embodiment scores were higher in the hand condition than the prosthesis condition, suggesting there was a stronger experience of these when controlling the virtual prosthesis via their own hand.

To test whether there is an effect for ownership, agency, and overall embodiment subscale scores were compared with respective control subscale scores. A Bonferroni correction was applied ( $\alpha \text{ value}/2 = p < .025$ ) for determining significance. Data was not normally distributed so the Wilcoxon test for significance was used. For the prosthesis condition there was a significantly higher ownership score than ownership control score ( $Z = -3.910, p < .001$ ), significantly higher agency score than agency control score ( $Z = -4.734, p < .001$ ), and significantly higher embodiment score than embodiment control score ( $Z = -4.596, p < .001$ ). Therefore, this means that all embodiment measures were endorsed significantly higher than their respective control questions measures, suggesting the presence of ownership, agency, and embodiment. For the hand condition there was a significantly higher ownership score than ownership control score ( $Z = -4.793, p < .001$ ), significantly higher agency score than agency control score ( $Z = -4.745, p < .001$ ), and significantly higher embodiment score than embodiment control score ( $Z = -4.782, p < .001$ ).

The relationship between ownership and agency scores was explored through correlations see Figures 94-95 for these relationships in both conditions.

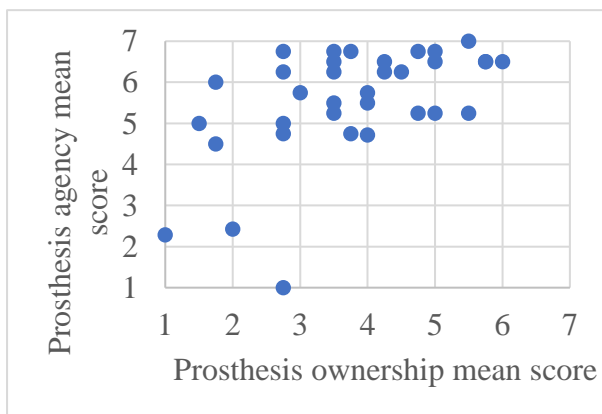


Figure 94. Positive association between ownership and agency scores in the prosthesis condition.

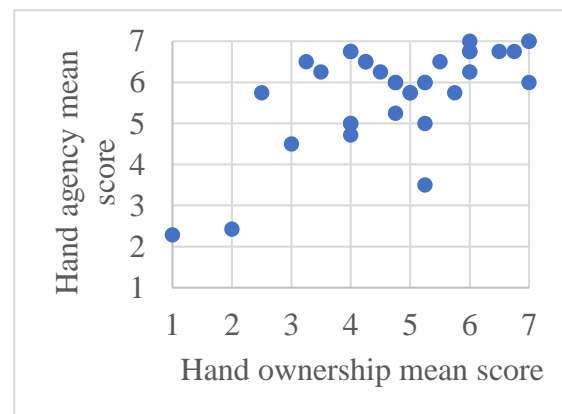


Figure 95. Positive association between ownership and agency scores in the hand condition.

As data was not normally distributed, Spearman’s rho was calculated, with a significant positive correlation between ownership and agency scores for the prosthesis condition ( $r_s = .451, p = .006$ ). Similarly, a positive correlation was also found for the hand condition ( $r_s = .421, p = .009$ ). These findings suggest that ownership and agency were not independent factors for both conditions.

**5.3.1.2 Statistical findings between conditions.** Ownership and Embodiment were normally distributed so a t-test was conducted for these, whereas agency was not normally distributed, so a Wilcoxon test for significance was conducted. Comparing between experimental conditions there was a significantly higher ownership ( $t(30) = -4.478, p < .001$ ) and embodiment ( $t(30) = -1.753, p = .045$ ) score in the hand condition than the prosthesis condition, but no significant difference for the agency score, ( $Z(30) = -1.422, p = .078$ ) between conditions.

**5.3.1.3 Order effects descriptive and inferential statistics.** Counterbalancing of conditions was utilised to avoid order effects but to check this, mean scores were compared between the first condition (i.e., the first experiment which could be the prosthesis or hand condition) and the 2<sup>nd</sup> condition. See Figure 96 for descriptive statistics for scores based on order of experimental condition (i.e., first or second time they participated in the experiment).

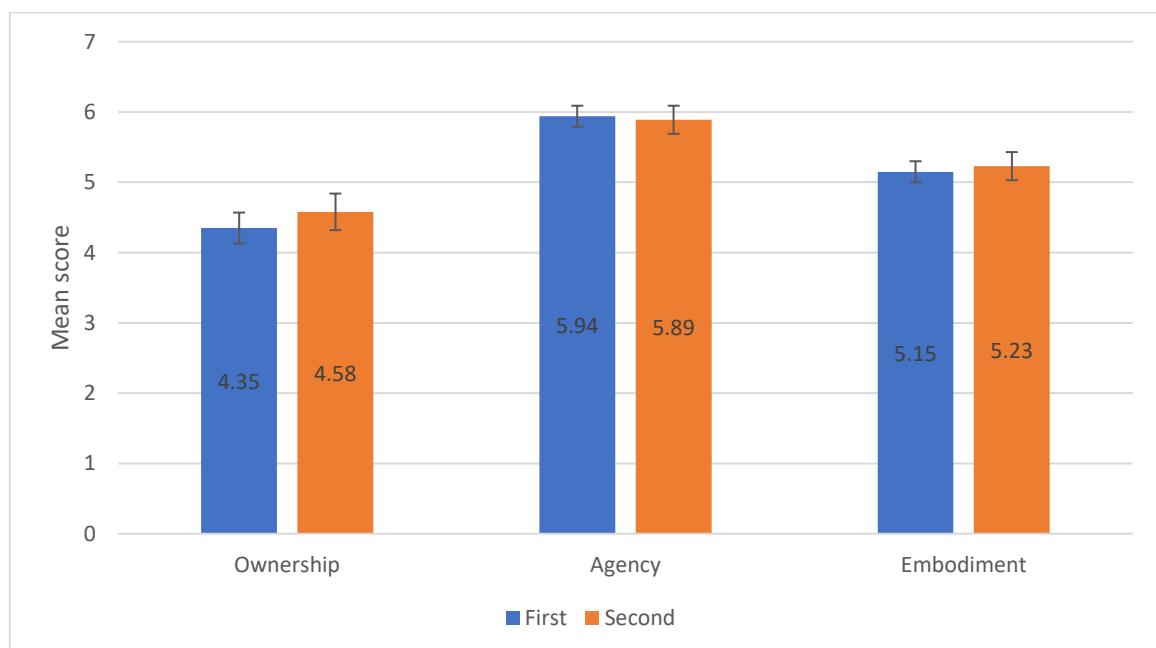


Figure 96. Mean sub-scale scores for ownership, agency, embodiment for the first and second conditions, with error bars representing the Standard Error.

Figure 96 shows that for ownership, agency, and embodiment there are similar means between the first condition and second condition, potentially suggesting order of conditions had no impact on findings.

For inferential statistics, Ownership and Embodiment were normally distributed so a t-test was conducted, whereas agency was not normally distributed so a Wilcoxon test for significance was conducted. A non-significant difference between condition order was found for ownership ( $t(30) = -7.19, p = .478$ ), a non-significant difference for the agency score between conditions ( $Z = -0.092, p = .927$ ), and a non-significant difference for embodiment between conditions was found ( $t(30) = -0.406, p = .688$ ). This suggests that the order in which experiments were conducted did not have an effect on questionnaire responses, and therefore order was not considered in subsequent analyses.

**5.3.2 Skin Conductance responses.** Skin conductance was collected during the experiment and until the whole 10-second period of the virtual threat (i.e., a virtual knife dropping down between the fingers of the hand and then remaining still) was completed. There were concerns that measuring any response during this latter period may not specifically capture a response to the knife threatening the hand so the behaviour of skin conductance, both before and during the threat period, was explored.

To assess the skin conductance overall and identify when on average it started rising and when it stopped rising, each second of the 10-second threat period was individually analysed to calculate percentage of participants for each of these. Started rising is determined from a visual observation of when the skin conductance value first started rising using the criteria of it needing to rise beyond 0.01 microsiemens to be counted. This criterion was used to be comparable to the minimum threshold setting used by the AcqKnowledge software to identify skin conductance responses (SCRs).

See Figure 97 for percentage of participants in each of the 10-second threat period where skin conductance started rising and also where it stopped rising, (i.e., a plateau was observed). No participant's skin conductance value continued raising after 9 seconds so this is not included on the graph.

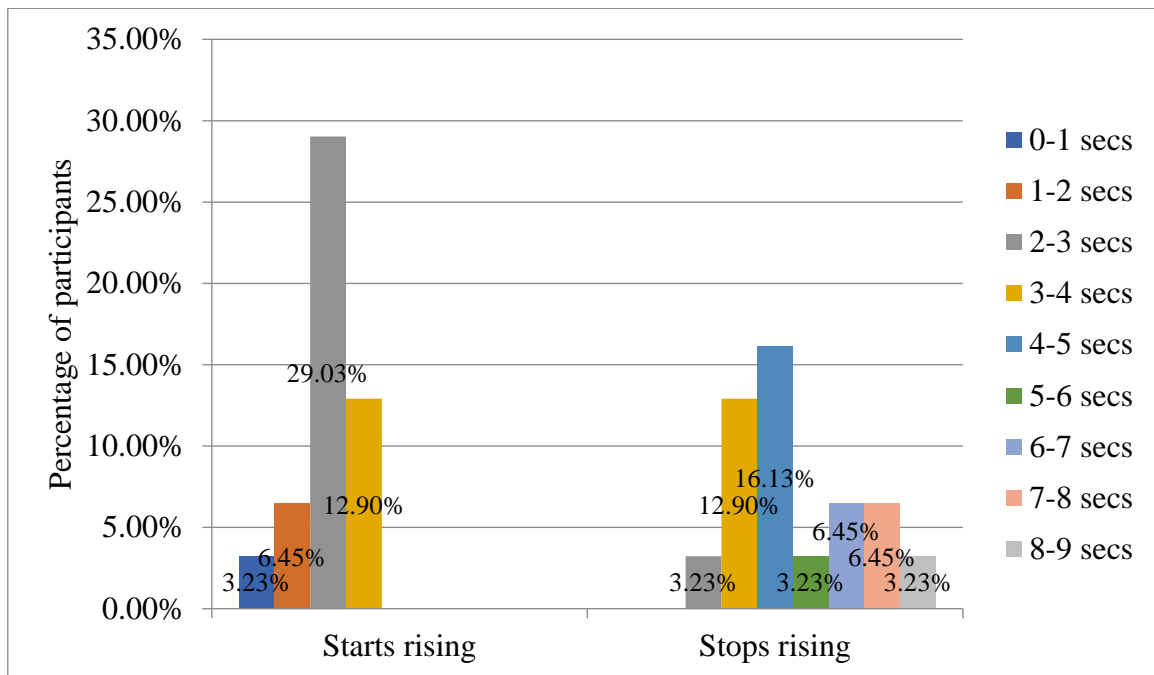


Figure 97. Percentage of participants in the prosthesis condition for each second during the 10-second threat period where skin conductance starts rising and stops rising.

Based on the criteria applied, 45.16% (14) of participants did not display an observable rise. Out of those who did, the highest prevalence (29.03%) occurred during the period of 2-3 seconds, then 3-4 seconds. Only limited number of participants displayed a rise during the 1<sup>st</sup> or 2<sup>nd</sup> second, representing 1 and 2 participants, respectively. Also, the highest percentage (16.13%) of participants stopped rising between 4-5 seconds, with the next highest (12.90%) at 3-4 seconds.

See Figure 98 for percentage of participants in each of the 10-second threat period where skin conductance started rising and also where it stopped rising, (i.e., a plateau was observed). No participant's skin conductance value continued raising after 9 seconds so this is not included on the graph.

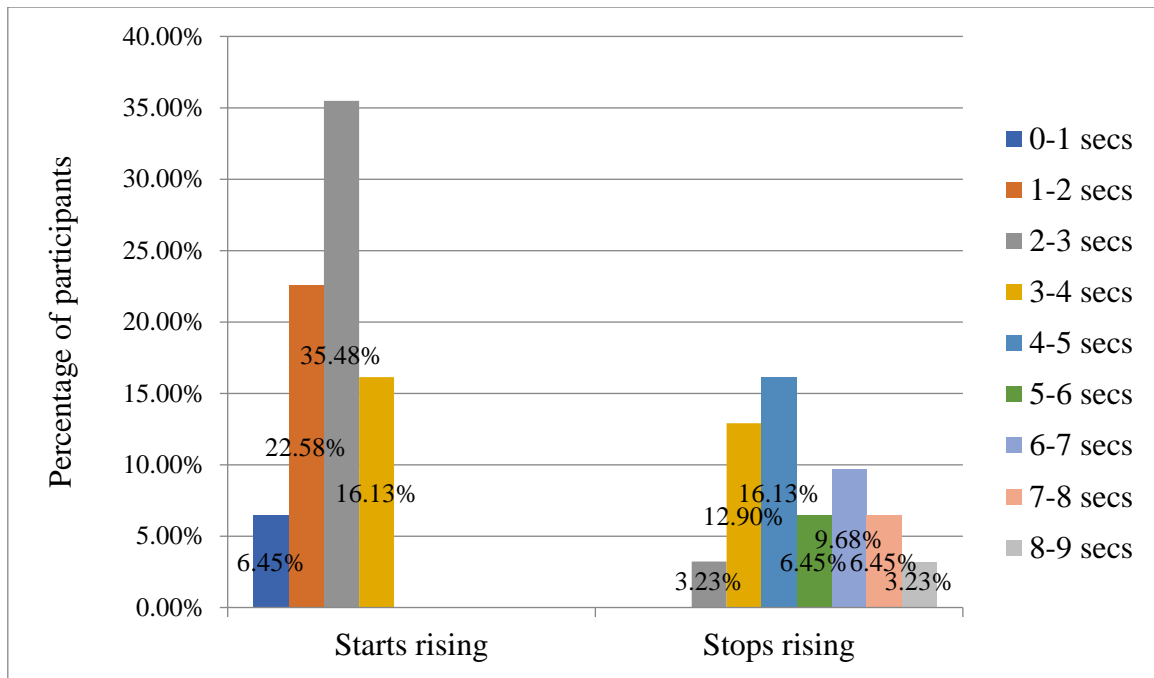


Figure 98. Percentage of participants in the hand condition for each second during the 10-second threat period where skin conductance starts rising and stops rising.

Based on the criteria applied, 19.36% (6) of participants did not display an observable rise. Out of those who did, the highest prevalence (35.48%) occurred during the period of 2-3 seconds, then 3-4 seconds. Only limited number of participants displayed a rise during the 1<sup>st</sup> or 2<sup>nd</sup> second, representing 1 and 2 participants, respectively. Also, the highest percentage (16.13%) of participants stopped rising between 4-5 seconds, with the next highest (12.90%) at 3-4 seconds. The majority of participants' skin conductance rise stopped rising from 4-5 seconds so the period up to here should be focused on. However, the next second period of 5-6 seconds is also included to see on average how the skin conductance changes.

Average and highest value of skin conductance were analysed on AcqKnowledge software for time bins during when the hand is moving (*Hand moving*), after hand movements have completed but there is no threat presented (*Hand still*), and when there is a threat presented (*Threat*). The specific point of interest is after when the knife animation is first presented so this is counted as 0 seconds, with multiple separate 1 second periods analysed before and after this point. Hand moving *-4 to -3 secs* and *-3 to -2 secs* represents the final 2 seconds of when the hand is moving. See Figure 99 for the mean skin conductance average scores (i.e., the average value within the period of time) for multiple 1 second periods split per condition.

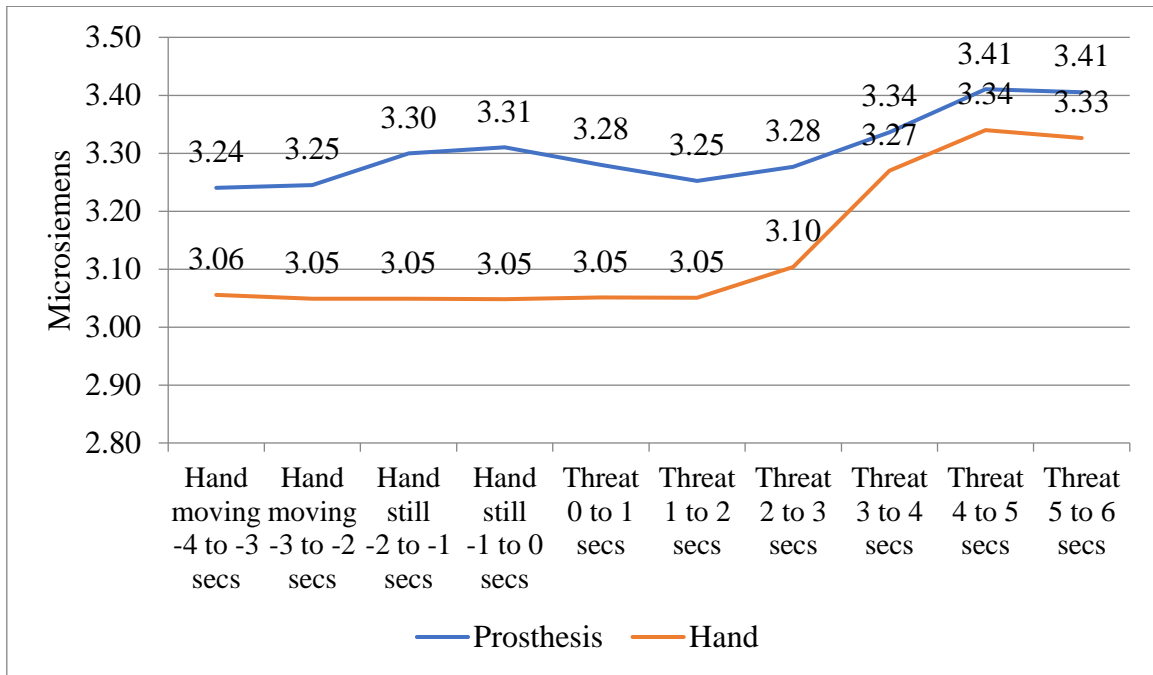


Figure 99. Skin conductance average scores across time bins for hand moving, hand still, and threat split for each condition.

See Figure 100 for the mean skin conductance highest scores (i.e., the highest value within the period of time) for multiple 1-second periods split per condition.

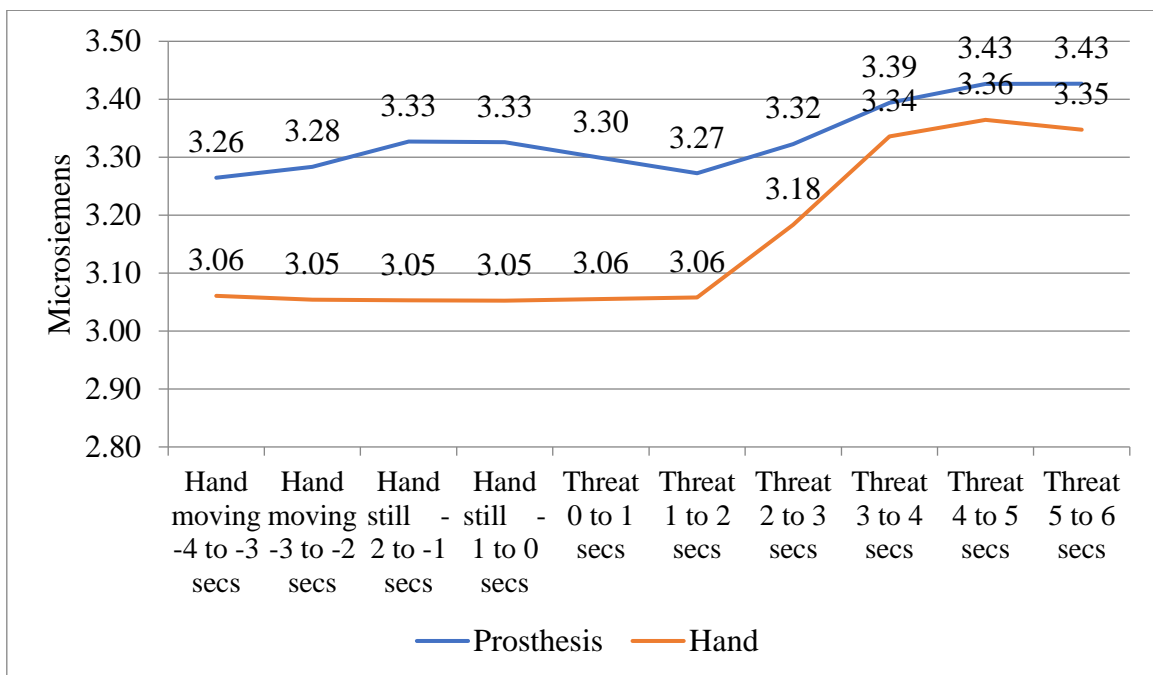


Figure 100. Skin conductance highest scores across time bins for hand moving, hand still, and threat split for each condition.



**5.3.2.1 Skin conductance descriptive and inferential statistics.** As not all participants displayed an SCR, based on analysis software criteria, an alternative but similar SCR value was used for all participants by taking the highest value in the experimental period during the knife drop (*Experimental highest*) minus the average (SCL) in the 2 seconds before (*Experimental baseline*). This is termed *Basic SCR*. See Table 23 for descriptive statistics for various skin conductance scores, including the average level while hand is still (experimental baseline SCL), the highest value during the first 5 seconds of the threat period (experimental highest), and the SCR amplitude (i.e., how much the SCL rises by between the baseline and highest value, Basic SCR).

Table 23

*Median and interquartile range skin conductance scores for experimental baseline, experimental highest, and skin conductance responses (split per condition)*

Condition	Exp baseline SCL		Exp highest		Basic SCR	
	<i>Mdn</i>	<i>IQR</i>	<i>Mdn</i>	<i>IQR</i>	<i>Mdn</i>	<i>IQR</i>
Prosthesis	2.64	3.18	2.82	3.27	0.18	0.09
Hand	2.69	3.24	3.07	3.59	0.38	0.35

*Note.* IQR = interquartile range; Exp baseline SCL = SCL average value during 2 seconds before knife animation (threat period); Exp highest = highest value during threat period; Basic SCR = Exp highest minus Exp baseline SCL.

Table 23 shows that Exp baseline value in the prosthesis condition is almost identical to the hand condition, whereas the highest SCL is noticeably higher in the hand condition. Similarly, the Basic SCR value is higher in the hand condition.

To first test whether there was a significant SCR within each condition, the highest SCR value was compared with the experimental baseline SCL (i.e., the difference between these is the Basic SCR). Data was not normally distributed so the Wilcoxon test for significance was used. There was a significantly higher experimental highest SCR than the experimental baseline SCL for both the prosthesis condition ( $Z = -3.763, p < .001$ ) and hand condition ( $Z = -4.586, p < .001$ ), suggesting there was a significant response to the knife animation.

**5.3.2.2 Ownership relationship with SCR.** To check if there is a relationship between ownership and SCR, Spearman's rho was calculated. There was no correlation between ownership and SCR for the prosthesis condition ( $r_s = .079, p = .337$ ) and no correlation for the hand condition ( $r_s = -.250, p = .088$ ), suggesting higher responses to the knife did not reflect a higher level of subjective ownership.

**5.3.2.3 Ownership differences depending on presence of SCR (rise vs no rise).** To further check if a higher level of ownership resulted in a higher SCR, the sample was split based on whether they displayed a SCR ('rise' group) or not ('no rise' group). This was determined by checking individual values and whether the SCR was at least 0.01 microsiemens (i.e., a rise of 0.01ms between the average SCL baseline and highest SCL value within 5 seconds of the threat period). As normality assumptions were met, independent t-tests were conducted. For the prosthesis condition, the rise group's ownership score ( $M = 4.02$ ) was not significantly higher than the no rise group ( $M = 3.79$ ), ( $t(29) = -0.498, p = .311$ ), further suggesting higher responses to the knife did not reflect a higher level of subjective ownership. Similarly, for the hand condition, the rise group's ownership score ( $M = 5.05$ ) was not significantly higher than the no rise group ( $M = 5.02$ ), ( $t(29) = -0.069, p = .473$ ), suggesting higher responses to the knife did not reflect a higher level of subjective ownership.

**5.3.2.4. Statistical findings between conditions.** To test whether the Basic SCR value is different between conditions, with data being not normally distributed the Wilcoxon test for significance was used. No significant difference was found between the prosthesis and hand condition ( $Z = -1.509, p = .066$ ), suggesting that SCR values were overall similar across conditions.

**5.3.3 Qualitative responses to questionnaires.** A Content Analysis was conducted on qualitative responses provided in the questionnaires (free responses on their experience of the virtual prosthesis) to see if experience of the virtual prosthesis could be captured in a different way than questions. The analysis identified categories which were grouped into themes. As a reminder, the question given to participants was:

*Please can you freely describe how you felt towards the virtual prosthesis during the hand movements.*

**5.3.3.1 Prosthesis condition responses.** See Table 24 for a summary of qualitative responses provided by participants for the prosthesis condition including categories and broader themes, along with the number and percentage of participants who noted each category. See Appendix X for the data.

Table 24

*Themes and categories identified from qualitative responses to the prosthesis condition questionnaire*

Categories identified	<i>n</i>	%
Realism		
Felt realistic	2	6.45
Control		
Felt in control	14	45.16
Felt in control with my mind	2	6.45
Moved on its own	1	3.23
Difficult/ uncomfortable to control	11	35.48
Limited control	1	3.23
Accuracy		
Accuracy issues	5	16.13
Matching hand to virtual hand	1	3.23
Responsiveness/Speed of hand		
Limited speed of hand	3	9.68
Noticeable delay	1	3.23
Not entirely responsive	3	9.68
Ownership		
No feelings towards hand	1	3.23
Not part of me/my body	4	12.90
Slightly part of me	2	6.45
More my hand as progressed	1	3.23
Appearance encouraged ownership	1	3.23
Extension of my body	1	3.23
General feelings		
Felt present in the game	2	6.45
Felt strange	2	6.45
Knife		
Enjoyed/ amazing experience	2	6.45
Worry about knife hurting hand	1	3.23

The analysis revealed for the prosthesis condition numerous codes/subcategories which were split into grouping categories for interpretation. Those most relevant to the experiment are mentioned below.

**Realism.** Only 2 participants noted that the prosthesis felt realistic. Whilst this is a very small number, this was salient enough to mention as a free response and no participants mentioned it did feel realistic.

**Control.** About half of the sample noted feeling in control which highlights the feeling of agency observed within this condition. However, about a third of the sample felt the prosthesis was difficult or uncomfortable to control and a further participant noting the limited control with the prosthesis. Whilst this does not directly reference ownership, this could be an aspect of controlling the prosthesis with muscle flexes which diminishes ownership, at least for some participants. In addition, one participant mentioned their prosthesis moved on its own which may have disrupted their feeling of agency or ownership.

**Responsiveness/Speed of hand.** This area is relevant as could impact on embodiment feelings, in particular agency. A small number of participants did note the slowness and limited responsiveness of the hand. Also, of relevance, despite being only one participant, is the mention of a noticeable delay with the hand. The inherent electromechanical delay is in addition to the latency of the motion tracking which was hoped not to directly influence findings, but there may be an individual difference of awareness of such a delay.

**Ownership.** Notably only small number of participants mentioned the prosthesis feeling part of them in some way.

**Accuracy.** A limited number of participants mentioned there being accuracy issues which seemingly had enough saliency to specifically mention, although they do not directly refer to impact on embodiment.

**Knife.** Whilst only one person mentioned the knife here, they noted their concern for it hurting the hand, which suggests some level of ownership being related to SCR.

**5.3.3.2 Hand condition responses.** See Table 25 for a summary of qualitative responses provided by participants for the hand condition including categories and broader themes, along with the number and percentage of participants who noted each category (See Appendix X for the data).

Table 25

*Themes and categories identified from qualitative responses to the hand condition questionnaire*

Categories identified	<i>n</i>	%
Realism		
Felt realistic	6	19.35
Felt unnatural	1	3.23
Control		
Felt in control	6	19.35
Felt in control with my mind	1	3.23
Easy or comfortable to control	3	9.68
Accuracy		
Accuracy issues	11	35.48
Hand accurate	5	16.13
Responsiveness/Speed of hand		
Limited speed of hand	1	3.23
Noticeable delay	1	3.23
Hand responsive/limited delay	4	12.90
Ownership		
No feelings towards hand	2	6.45
Not part of me/my body	2	6.45
Slightly part of me	4	12.90
Felt like my hand/part of my body	5	16.13
Extension of my body	1	3.23
General feelings		
Limited hand movements	5	16.13
Felt present in the game	1	3.23
Felt strange in the beginning	1	3.23
Enjoyed/ amazing experience	4	12.90
Knife		
Worry about knife hurting hand	1	3.23
Scared at first then OK	1	3.23
Didn't focus on knife when dropped	1	3.23
Felt nervous when dropped	1	3.23

The analysis revealed for the hand condition numerous codes/subcategories which were split into grouping categories for interpretation. Those most relevant to the experiment are mentioned below.

**Realism.** Whilst still a relatively small number of participants, a greater number compared to the prosthesis condition noted that the prosthesis felt realistic. This would be expected with anatomical hand control.

**Control.** Interestingly less participants than in the prosthesis condition noted feeling in control, however this may be due to control of their own hand being self-evident and not

worth mentioning. Also, instead of mentioning the control method being difficult or uncomfortable some participants mentioned this was easy/comfortable to control. This might be expected to be one aspect favouring ownership in this condition.

**Responsiveness/Speed of hand.** A small number of participants noted the hand being responsive with limited delay, however as with the prosthesis condition one participant mentioned the delay with the hand. This means they were observant of the delay in motion tracking.

**Ownership.** Whilst a small number of participants noted a lack of ownership, as with the prosthesis condition, there was double the number who noted feeling some form of ownership, compared to the prosthesis condition.

**Accuracy.** In comparison to the prosthesis condition, double the number of participants noted the accuracy issues. These may have been more salient in this condition due to the fine finger movement and sensory feedback making accuracy discrepancies be more obvious.

**Knife.** Similar to the prosthesis condition a couple of participants noted their concern with knife suggesting some level of ownership being related to SCR.

**5.3.4 Qualitative responses to additional questions after the experiment.** As a reminder, 4 additional questions were given to participants after completion of the whole experiment. The questions were:

*Q1) Were you consciously aware of the accuracy of the virtual hand (for example, whether fingers were moving correctly or in the wrong position)?*

*Q2) Did the accuracy influence your experience in terms of the questions you completed?*

*Q3) Did having your hand over or under the table influence your experience in terms of the questions you completed?*

*Q4) Did you feel the knife was a threat to the hand?*

For each question, responses were analysed with Content Analysis for identifying specific categories discussed in addition to calculating percentages of frequencies for each type of response (See Appendix Y for the data).

For question 1, whether and how much someone was aware of the accuracy of the virtual prosthesis was assessed. Responses emerged as either “yes”, “a little”, or “no”. These were when no specific condition was mentioned. However, some related their response to a

specific condition (i.e., when controlling via their own hand or the prosthetic hand). These were coded with the respective response, for example ‘Yes (Prosthetic)’ is when the participant was aware of accuracy but specifically during the prosthesis condition. See Table 26 for a summary of percentages of awareness of accuracy.

Table 26

*Awareness of accuracy (Q1)*

	Yes	A little	No	Prosthesis		Hand	
				Yes	A little	Yes	A little
%	75.86	17.24	6.90	13.79	3.45	31.03	3.45

In addition, when answering question 1 some participants detailed the specific aspect of accuracy, they were aware of. These were categorised accordingly – “Flickering” is when participants noted the fingers of the virtual prosthesis flickering back and forth rapidly, “Moving incorrectly” is when the fingers did not follow the appropriate movement (i.e., when either closing, opening, or remaining still), “Vanish into table” was when part of the hand vanished into the virtual table, “Hand flipping” is when the hand rotated approximately 180 degrees to an incorrect position, and “Latency” is when participants noted a delay in them controlling the virtual prosthesis and seeing the hand move. See Table 27 for a summary of percentages of information given by participants about accuracy issues.

Table 27

*Accuracy awareness information given by participants (Q1)*

Accuracy issue	%
Flickering	10.34
Moving incorrectly	37.93
Vanish into the table	3.45
Hand flipping	3.45
Latency	3.45

For question 2, participants responded on whether and how much their awareness of accuracy issues impacted on their responses to embodiment questions. As previously, responses were either “Yes”, “No”, or “A little”. However, some related this impact to either

the hand or prosthesis control condition, or to either the questions focusing on ownership “Ownership” or agency “Agency”. These were coded with the respective response. See Table 28 for a summary of percentages of impact of accuracy reported by participants.

Table 28

*Impact of accuracy (Q2)*

	Yes	A little	No	Ownership		Prosthesis		Hand	
				Yes	Agency	Yes	A little	Yes	A little
%	27.59	24.14	48.28	6.90	3.45	0.00	0.00	6.90	0.00

As previously, when answering question 2 some participants detailed the specific aspect of accuracy issue which had impacted them. These were categorised accordingly – categories were the same as for question 1 (Table 26) except for “Hand incorrect position” which is when the virtual hand was in a noticeably incorrect position relative to the participant’s hand or prosthetic hand. See Table 29 for a summary of percentages of information given by participants about accuracy impact issues.

Table 29

*Accuracy impact information given by participants (Q2)*

Accuracy issue	%
Flickering	3.45
Moving incorrectly	3.45
Vanish into table	0.00
Hand incorrect position	0.00
Latency	3.45

For question 3, participants responded on whether and how much the position of their anatomical hand (above or below the desk) impacted on their response to questions. As previously, responses were either “Yes”, “A little”, or “No”. See Table 30 for a summary of percentages of impact of hand positive above/below table.



Table 30

*Impact of the hand placement (Q3)*

Impacted	%
Yes	10.34
A little	6.90
No	82.76

When participants did report an impact, some provided reasons for this. These were categorised accordingly – “Harder to control prosthesis under table” relates to the difficulty in controlling the prosthesis from flexing arm muscles under the table, “See hand on table and feel it” relates to the benefit from the anatomical hand condition where the participant could feel the table combined with seeing the hand on it, and “Suggestion to improve: Rest hand on something over leg” was a suggestion provided for improving the discrepancy between the conditions, by including an equivalent feeling of resting their hand on the table from something above their leg where their hand was naturally placed. See Table 31 for a summary of percentages of reasons provided for the impact of hand placement.

Table 31

*Reasons given for the effect of hand placement (Q3)*

Impact of hand placement	%
Harder to control prosthesis under table	6.90
See hand on table and feel it	10.34
Suggestion to improve: Rest hand on something over leg	3.45

For question 4, participants reported whether and how much they perceived the virtual knife to be a threat to the virtual hand. As previously explained, some participants mentioned the knife was a threat but in a specific condition. See Table 32 for a summary of percentages of whether the knife was perceived to be a threat.

Table 32

*If the knife was a threat (Q4)*

	Yes	A little	No	Yes	
				Prosthesis	Hand
%	34.48	13.79	51.72	10.34	20.69

When the knife was not perceived as a threat, some participants detailed reasons for this. These were categorised accordingly, either the knife not feeling real, having knowledge that either the hand or the knife was not real, the knife dropped slower than expected, feeling that they had to either avoid the knife or pick it up after dropping, or that the knife had no sound hitting the table. See Table 33 for a summary of percentages of reasons why the knife was not perceived to be a threat.

Table 33

*Reasons why the knife was not a threat (Q4)*

Reason	%
Not realistic	10.34
Knew hand or knife was not real	17.24
Slow	6.90
Thought had to pick it up or dodge	6.90
No sound	3.45

Those who felt the knife was not a threat provided suggestions for how to improve this. These were categorised as either that the knife should stab the hand, there should be multiple knives, the knife should make a sound when it hits the table, it should fall quicker, be larger, in a different position, or that the participant should have haptic feedback from feeling vibration when the knife hits the table. See Table 34 for a summary of percentages of suggestions to improve the knife as a threat.

Table 34

*How to improve the knife threat (Q4)*

Improvement	%
Stab hand	6.90
Multiple knives	3.45
Sound	17.24
Quicker	10.34
Larger	3.45
Different position	3.45
Vibration	3.45

**5.3.5 Accuracy analysis.**

**5.3.5.1 Accuracy descriptive and inferential statistics within conditions.** See Table 35 for a summary of results from the accuracy analysis, including the average inaccuracy scores for various categories, along with the total inaccuracy score for each condition. For convenience the following acronyms are used:

- *Virtual hand vanishes* = HV.
- *Virtual hand switches* = HS.
- *Virtual hand incorrect position* = HIP.
- *Virtual hand in-appropriate movement* = HIM.
- *Incorrect virtual fingers* = IF.
- *Virtual fingers flickering* = FF.

Table 35

*Summary of accuracy analysis*

Accuracy issue	<i>n</i> (%)		Average instance	
	Prosthesis	Hand	Prosthesis	Hand
HV	0 (0)	0 (0)	0	0
HS	0 (0)	0 (0)	0	0
HIP	0 (0)	8 (28.57)	0	7.5
HIM	0 (0)	1 (3.75)	0	1
IF	18 (64.29)	15 (53.57)	25.83	21.6
FF	26 (92.86)	23 (82.14)	19.65	13
Total overall inaccuracy	27 (96.43)	23 (82.74)	36.15	23

*Note.* Average instance = the average number of times the accuracy issue occurred based only on those who experienced this (i.e., on average how many times there was an instance of the specific accuracy issue).

See Figure 101 for number of participants affected for separate categories and overall inaccuracy.

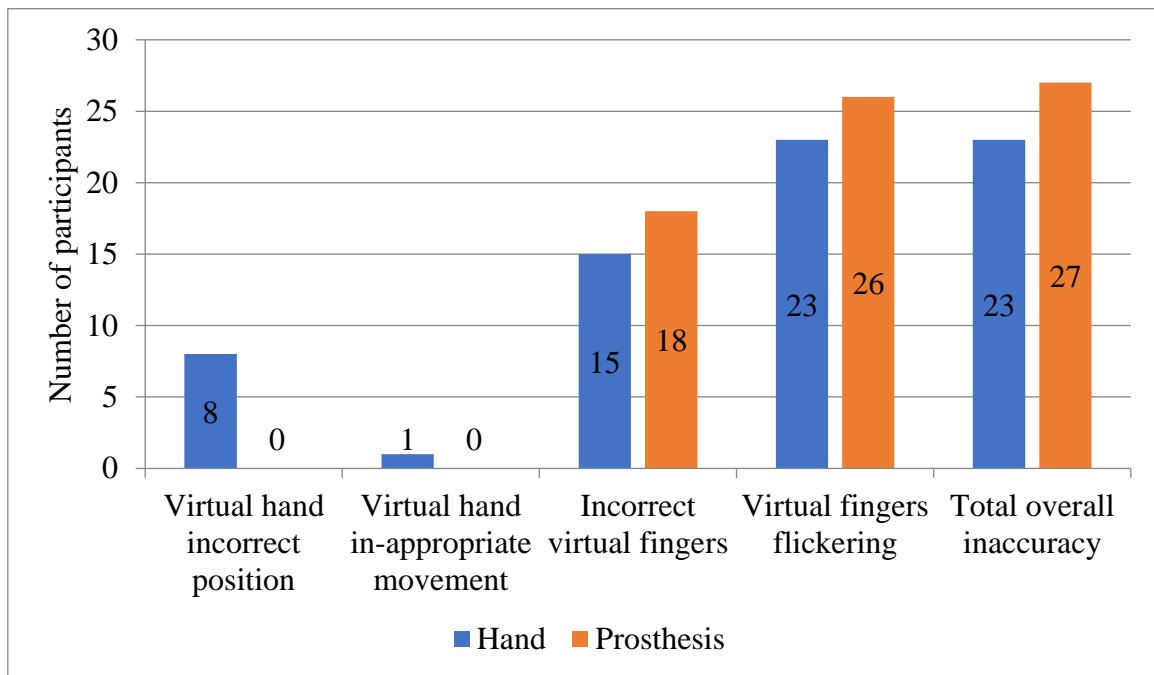


Figure 101. Number of participants who were affected by accuracy issues.

See Figure 102 for number of times there was a specific accuracy issue (i.e., the total number of instances for each).

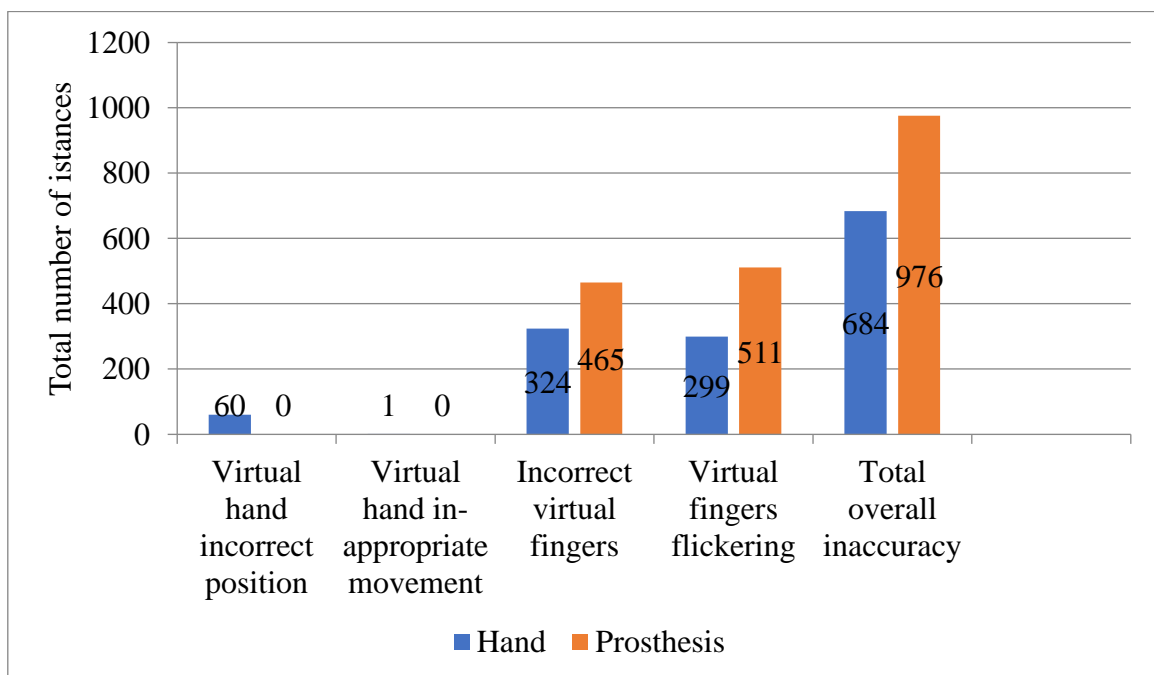


Figure 102. Number of times there was a specific accuracy issue.

See Figure 103 for number of instances on average participants experienced accuracy issues (based only on those participants who experienced inaccuracies).

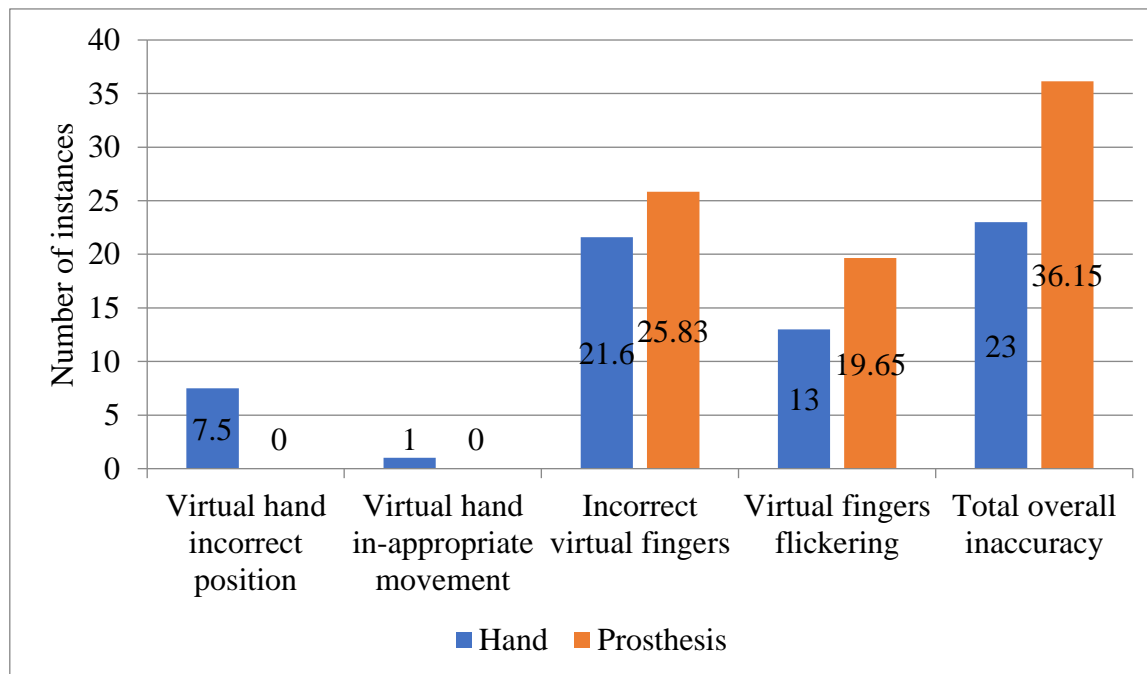


Figure 103. Number of instances on average participants experienced an accuracy issue.

To check if there is a relationship between total accuracy score and both questionnaire scores and SCR, and with data being not normally distributed, Spearman’s rho was calculated. With greater accuracy issues expected to reduce embodiment, all tests were one-tailed. See Table 36 for statistical results of all correlations for the prosthesis condition.

Table 36

*Spearman’s rho correlations between specific accuracy categories and questionnaire scores and SCR for prosthesis condition*

Accuracy issue	Ownership		Agency		Embodiment		Basic SCR	
	$r_s$	$P$	$r_s$	$p$	$r_s$	$p$	$r_s$	$p$
Incorrect virtual fingers	.002	.496	-.112	.285	-.047	.407	-.037	.426
Virtual fingers flickering	.025	.449	-.103	.301	-.044	.413	.067	.367
Total inaccuracy	.014	.471	-.076	.351	-.024	.453	-.032	.435

Note. Virtual hand incorrect position and virtual hand inappropriate movement had no correlation test was completed due to a variable having 0 values for all participants.

Table 35 suggests that for the prosthesis condition there is no significant relationship between having better or worse accuracy (for any specific category or overall score) and a higher or lower embodiment or response to the knife. See Table 37 for statistical results of all correlations for the hand condition.

Table 37

*Spearman's rho correlations between specific accuracy categories and questionnaire scores and SCR for the hand condition*

Accuracy issue	Ownership		Agency		Embodiment		Basic SCR	
	$r_s$	$p$	$r_s$	$p$	$r_s$	$p$	$r_s$	$p$
Virtual hand incorrect position	.080	.343	-.274	.079	-.082	.339	-.032	.437
Virtual hand in-appropriate movement	.048	.405	-.084	.335	.097	.312	.250	.100
Incorrect virtual fingers	-.153	.219	-.023	.454	-.014	.471	.218	.133
Virtual fingers flickering	-.041	.418	.159	.210	.126	.262	.100	.307
Total inaccuracy	-.081	.342	.024	.453	.083	.337	.137	.244

Similarly, Table 37 suggests that for the hand condition there is no significant relationship between having better or worse accuracy (for any specific category or overall score) and a higher or lower embodiment or response to the knife.

**5.3.5.2 Statistical findings between conditions.** See Figure 104 for median scores for individual categories and overall accuracy between conditions.

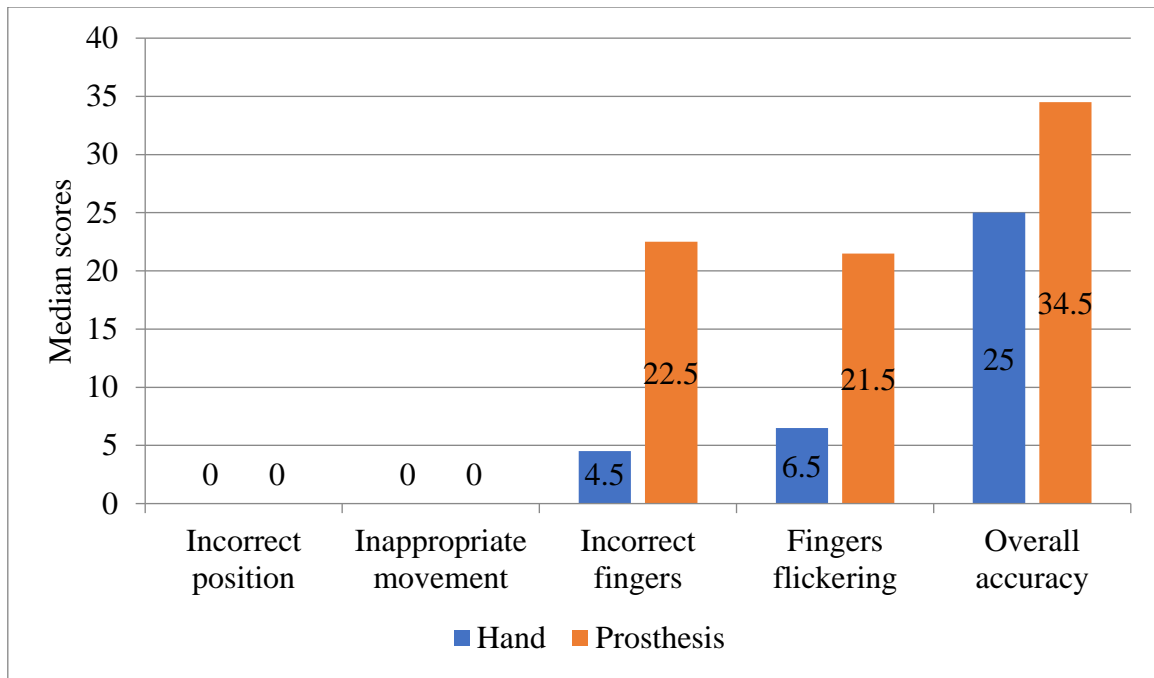


Figure 104. Median scores for individual categories and overall accuracy between conditions.

With data being not normally distributed, a Wilcoxon test for significance was conducted. With the unpredictable nature of the accuracy between each condition for these, and all subsequent tests which compare accuracy between conditions, two-tailed tests were conducted. Comparing total accuracy score between conditions there was no significant difference between the prosthesis and hand condition ( $Z = -1.378, p = .168$ ). This suggests that accuracy overall was not different across conditions. Exploring individual categories of accuracy, virtual hand in incorrect position was significantly greater in the hand condition than prosthesis condition ( $Z = -2.527, p = .012$ ), virtual hand inappropriate movement had no significant difference ( $Z = -1.000, p = .317$ ), incorrect virtual fingers had no significant difference ( $Z = -1.592, p = .111$ ), and virtual fingers flickering was significantly greater in the prosthesis condition than hand condition ( $Z = -2.016, p = .044$ ). Other categories not mentioned had no instances in both conditions so not statistical tests were completed. This suggests that there was a greater prevalence of hand in incorrect position during the hand condition, whereas finger flickering was more prevalent during the prosthesis condition.

**5.3.5.3 Further exploring the impact of accuracy on scores.** The non-significant difference between conditions in overall accuracy was further explored to encourage confidence in differences in scores (e.g., ownership) between conditions being due to the

experimental procedure rather than accuracy differences. Participants who had declared they were aware of, and been consciously impacted by the accuracy issues, were identified (those who answered ‘yes’ or ‘a little’ to Q2 after the experiment,  $N = 14$ ) and removed for a separate analysis (i.e., only those who did not report accuracy issues were compared across conditions,  $N = 14$ ). See Figure 105 for ownership, agency, and embodiment differences between conditions for only participants who declared no impact from accuracy.

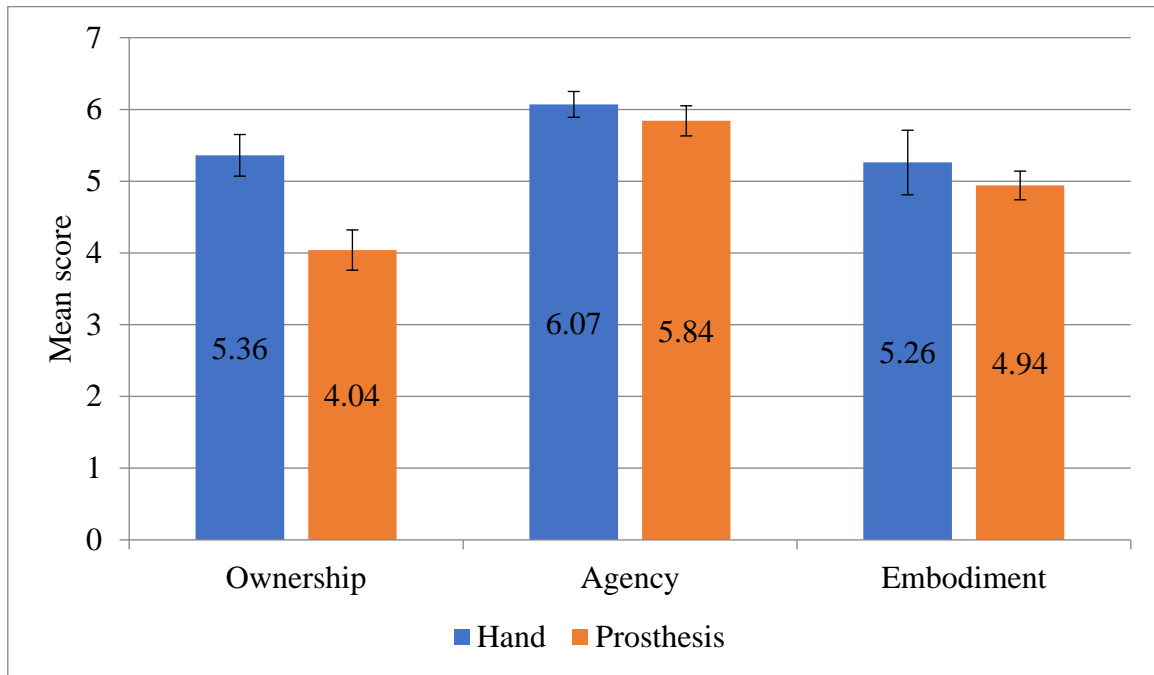


Figure 105. Ownership, agency, and embodiment differences between conditions for only participants who declared no impact from accuracy, with error bars representing the Standard Error.

Participants who reported no accuracy issues had significantly greater ownership in the hand condition ( $M = 5.36$ ) compared to the prosthesis condition ( $M = 4.04$ ), ( $t(13) = -3.944$ ,  $p = .001$ ), no significant difference for agency ( $t(13) = -1.149$ ,  $p = .136$ ), no significant difference for embodiment ( $t(13) = -0.587$ ,  $p = .284$ ), and no significant difference for SCR ( $Z = -0.659$ ,  $p = .255$ ). Also, notably there was still no significant difference between conditions for overall accuracy ( $t(13) = 1.705$ ,  $p = .112$ ). These findings are similar to the whole dataset with the sole difference being a significant difference for embodiment.

For the prosthesis condition, there were still no significant correlations between accuracy and ownership ( $r = -.263$ ,  $p = .182$ ), agency ( $r = -.260$ ,  $p = .185$ ), embodiment ( $r_s =$



-.350,  $p = .110$ ), and SCR ( $r_s = -.002$ ,  $p = .497$ ). For the hand condition, there were still no significant correlations between accuracy and ownership ( $r = -.092$ ,  $p = .377$ ), agency ( $r = -.212$ ,  $p = .233$ ), embodiment ( $r_s = .400$ ,  $p = .078$ ), and SCR ( $r_s = -.186$ ,  $p = .263$ ). These findings are comparable to the whole dataset except in the prosthesis condition the relationship for ownership is negative (positive for the whole dataset), and in the hand condition, agency and SCR have a negative relationship with accuracy (positive for the whole dataset).

To explore the potential impact of objective accuracy issues instead of subjective experience of these, a median split analysis of both the prosthesis and hand condition accuracy analyses was conducted to see if patterns are similar across groups. See Figure 106 for mean ownership, agency, and embodiment scores, split per condition, for participants who scored below the median ( $N = 14$ ) on total accuracy in the prosthesis condition.

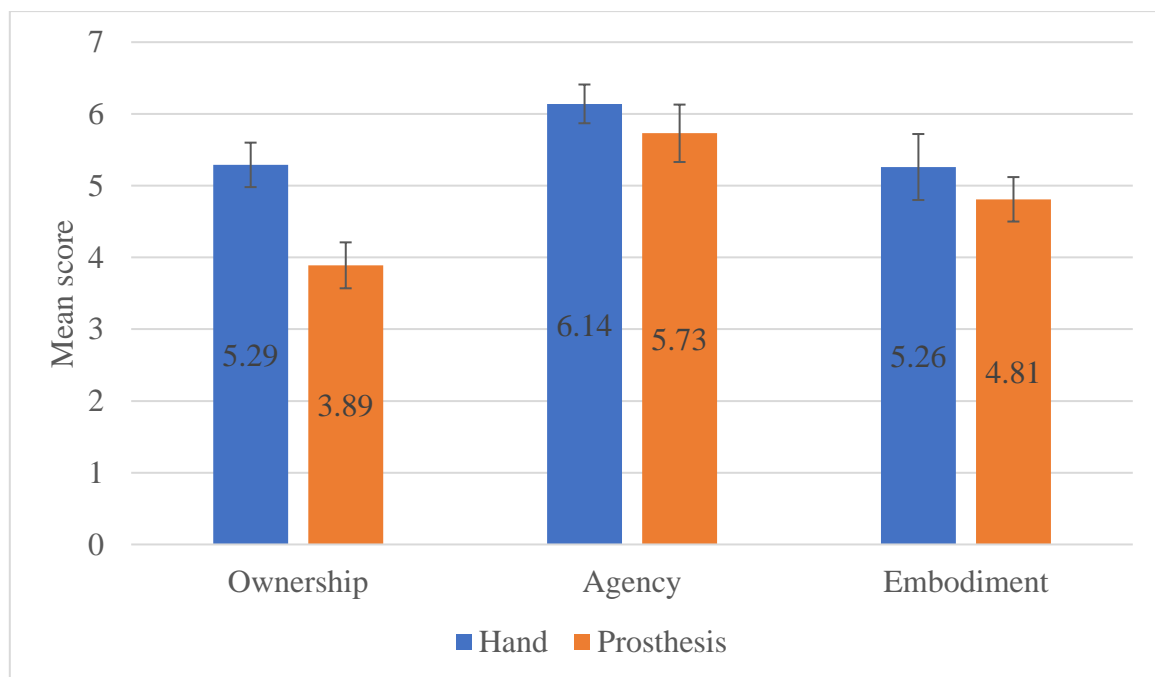


Figure 106. Mean ownership, agency, embodiment scores for participants who scored below the median on total accuracy for the prosthesis condition, with error bars representing the Standard Error.

Figure 106 suggests a greater difference for the ownership score between conditions compared to agency and embodiment. Supporting these descriptive statistics, the group with prosthesis inaccuracy below the median (i.e., low accuracy issues) had a significantly higher

ownership score in the hand condition than the prosthesis condition, ( $t(13) = -4.596, p < .001$ ), no significant difference for the agency score ( $t(13) = -1.629, p = .064$ ), and no significant difference for the embodiment score ( $t(13) = -0.800, p = .219$ ). In addition, no significant difference for SCR ( $Z = -0.659, p = .255$ ) was found between the prosthesis and hand conditions.

See Figure 107 for mean ownership, agency, and embodiment scores, split per condition, for participants who scored above the median on total accuracy in the prosthesis condition.

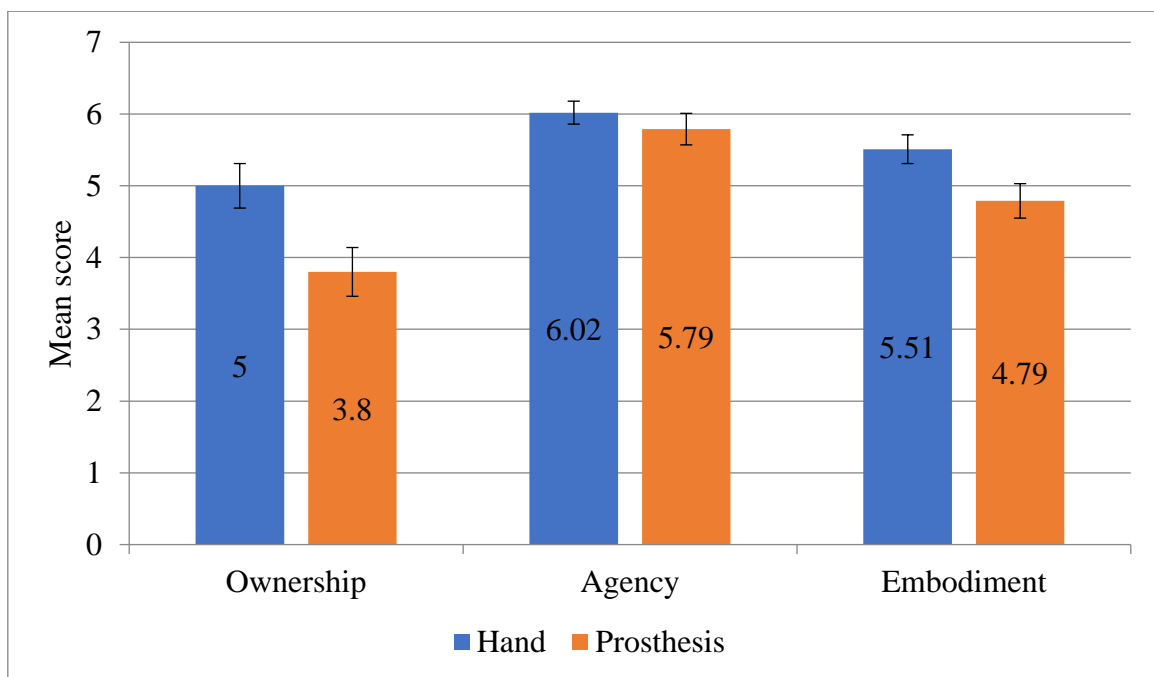


Figure 107. Mean Ownership, agency, embodiment scores for participants who scored above the median on total accuracy for the prosthesis condition, with error bars representing the Standard Error.

Similar to the previous group, Figure 107 suggests a difference for the ownership score between conditions compared to agency, but in comparison the difference in embodiment score between conditions appears larger. Supporting these descriptive statistics, the group with inaccuracy above the median (i.e., high accuracy issues,  $N = 14$ ) had a significantly higher ownership score in the hand condition than the prosthesis condition, ( $t(13) = -2.742, p = .009$ ), no significant difference for the agency score ( $t(13) = -1.179, p = .130$ ), and a significantly greater embodiment score for the hand condition than prosthesis

condition ( $t(13) = -2.472, p = .014$ ). In addition, no significant difference for SCR ( $Z = -0.785, p = .217$ ) was found between the prosthesis and hand conditions. These findings suggest that patterns of differences between conditions were mostly equivalent between the low and high prosthesis accuracy groups, with just a significant difference for embodiment for the high inaccuracy group.

See Figure 108 for mean ownership, agency, and embodiment scores, split per condition, for participants who scored below the median on total accuracy in the hand condition.

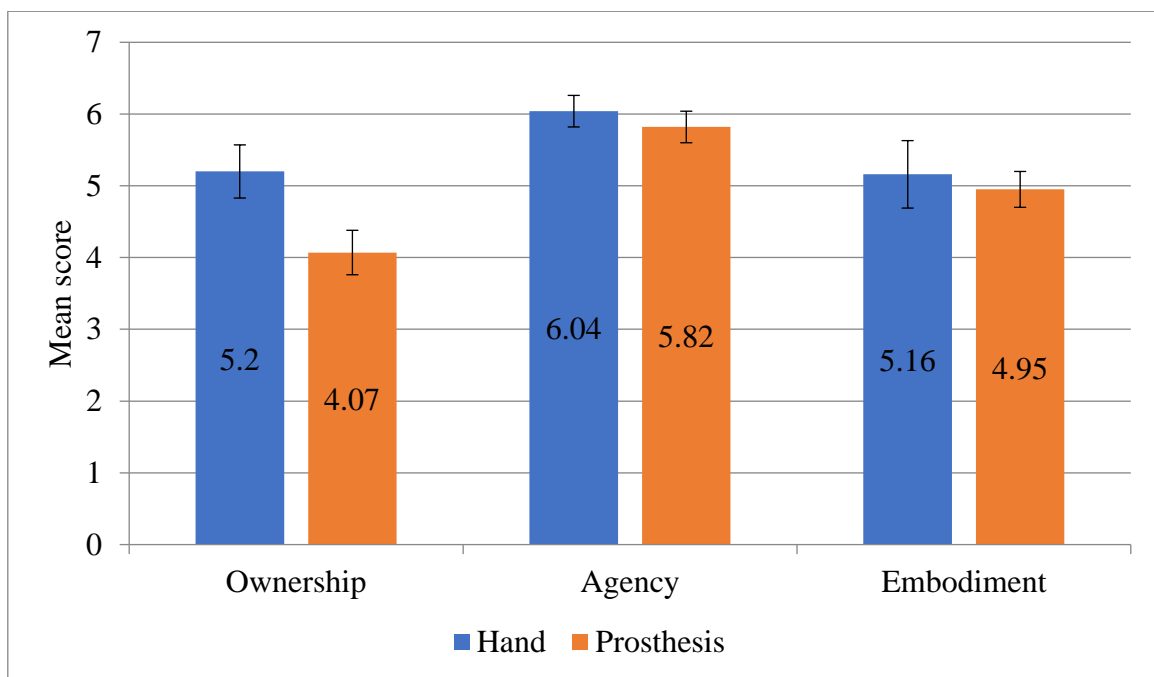


Figure 108. Mean Ownership, agency, embodiment scores for participants who scored below the median on total accuracy for the hand condition, with error bars representing the Standard Error.

Figure 108 suggests a greater difference for the ownership score between conditions compared to agency and embodiment. Supporting these descriptive statistics, the group with hand inaccuracy below the median (i.e., low accuracy issues) had a significantly higher ownership score in the hand condition than the prosthesis condition, ( $t(13) = -2.761, p = .008$ ), no significant difference for the agency score ( $t(13) = -1.125, p = .141$ ), and no significant difference for the embodiment score ( $t(13) = -0.382, p = .355$ ). In addition, no

significant difference for SCR ( $Z = -0.345, p = .365$ ) was found between the prosthesis and hand conditions.

See Figure 109 for mean ownership, agency, and embodiment scores, split per condition, for participants who scored above the median on total accuracy in the hand condition.

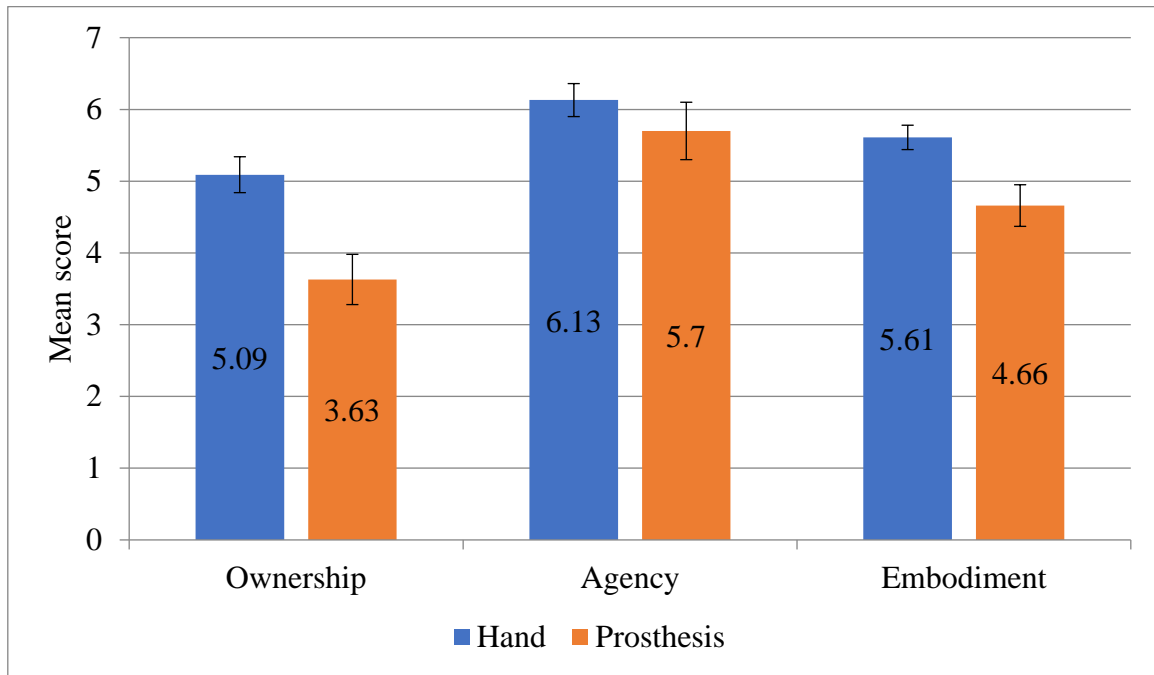


Figure 109. Mean ownership, agency, embodiment for participants who scored above the median on total accuracy for the hand condition, with error bars representing the Standard Error.

Similar to the previous group, Figure 109 suggests a difference for the ownership score between conditions compared to agency, but in comparison the difference in embodiment score between conditions appears larger. Supporting these descriptive statistics, the group with hand inaccuracy above the median had a significantly higher ownership score in the hand condition than the prosthesis condition, ( $t(13) = -4.352, p = .005$ ), no significant difference for the agency score ( $t(13) = -1.674, p = .059$ ), and a significantly higher embodiment score in the hand condition than the prosthesis condition ( $t(13) = -3.792, p = .01$ ). In addition, no significant difference for SCR ( $Z = -1.726, p = .042$ ) was found between the prosthesis and hand conditions. As with the prosthesis accuracy, these findings suggest that patterns of differences between conditions were mostly equivalent between the low and

high accuracy groups, with just a significant difference for embodiment for the high inaccuracy group.

As a final check of whether accuracy influenced findings, groups based on the median split were compared on their questionnaire and SCR scores for their respective condition (i.e., scores for the prosthesis condition were compared between those with low and high accuracy issues in the prosthesis condition) via an independent samples t-test. See Figure 110 for mean ownership, agency, and embodiment scores for participants who scored below and above the median on total accuracy for the prosthesis condition.

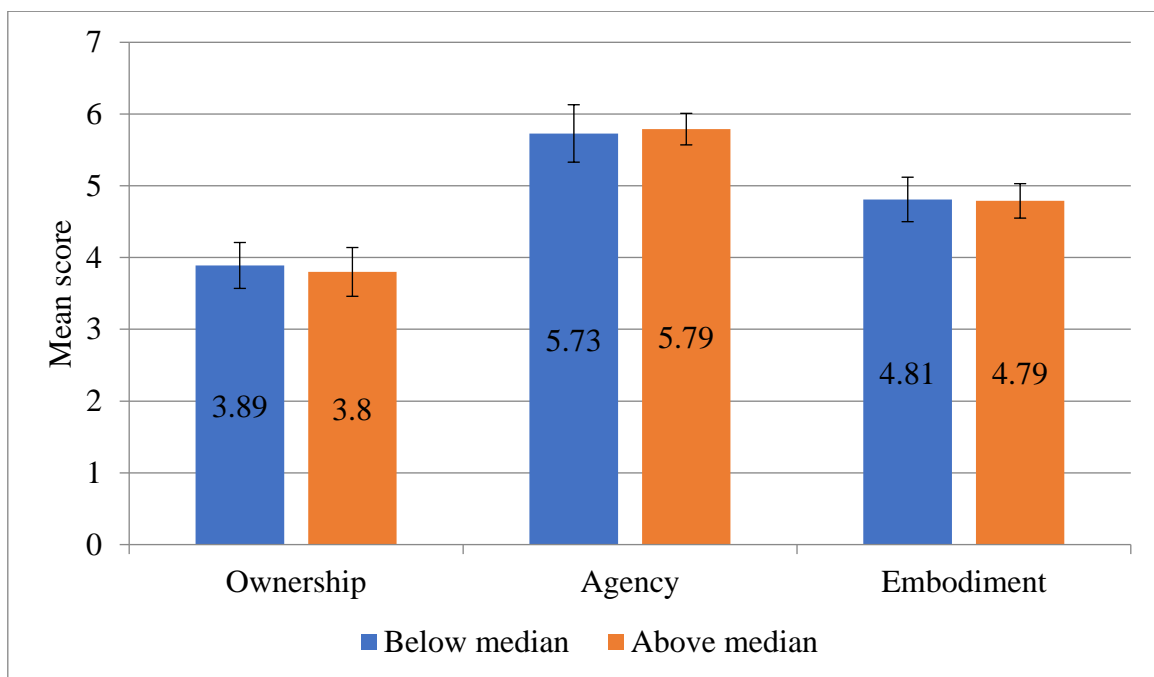


Figure 110. Mean ownership, agency, embodiment scores for participants who scored below and above the median on total accuracy for the prosthesis condition, with error bars representing the Standard Error.

Figure 110 suggests there are no differences between questionnaire scores based on whether the participant was below or above the media for accuracy issues. Supporting this, for the prosthesis condition, there was no significant difference for the ownership score ( $t(26) = 0.189, p = .426$ ), the agency score ( $t(13) = -0.117, p = .454$ ), and no significant difference for the embodiment score ( $t(26) = 0.046, p = .482$ ). In addition, there was no significant difference for SCR ( $t(26) = 0.296, p = .385$ ) between groups.

See Figure 111 for mean ownership, agency, and embodiment scores for participants who scored below and above the median on total accuracy for the hand condition.

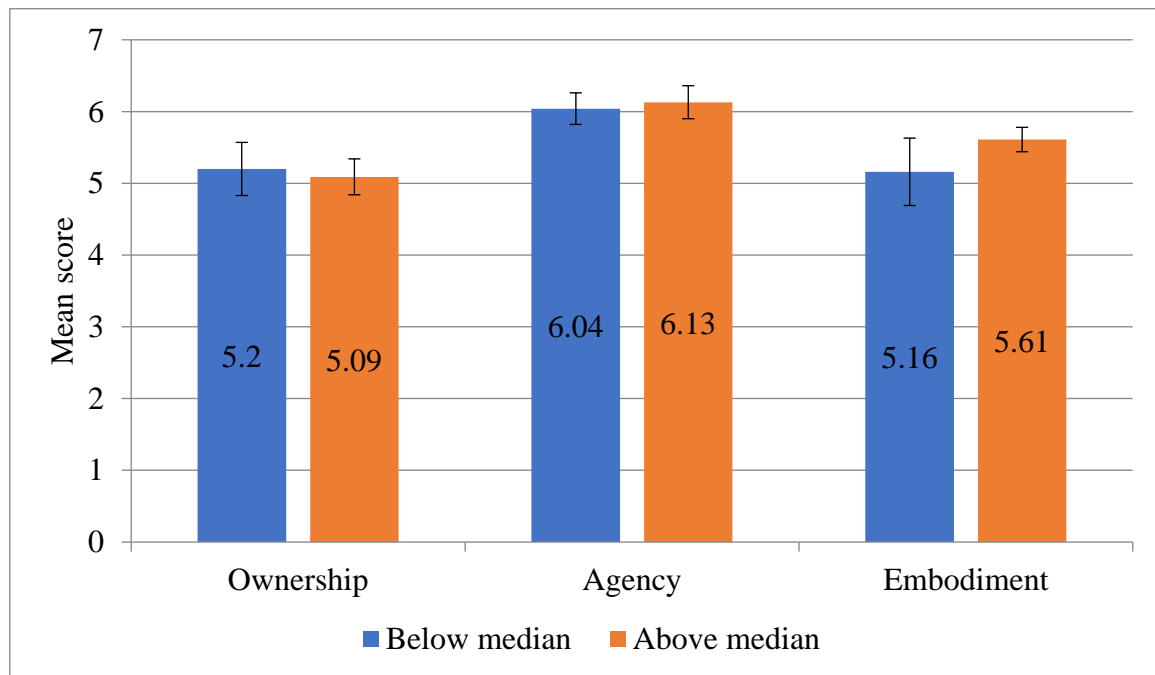


Figure 111. Mean ownership, agency, and embodiment scores for participants who scored below and above the median on total accuracy for the hand condition, with error bars representing the Standard Error.

Similarly, Figure 111 suggests there are no differences between questionnaire scores based on whether the participant was below or above the media for accuracy issues. Supporting this, for the hand condition, there was no significant difference for the ownership score ( $t(26) = 0.243, p = .405$ ), the agency score ( $t(13) = -0.281, p = .391$ ), and the embodiment score ( $t(26) = -0.891, p = .191$ ). In addition, there was no significant difference for SCR ( $t(26) = -0.952, p = .175$ ). Taken together, these results suggest higher or lower accuracy issues on the whole did not significantly impact any of the measures within both conditions.

## 5.4 Discussion

As a reminder the hypotheses for the study were as follows:

- H1: All subscale and embodiment scores will be significantly higher than their respective control subscale scores in both conditions

- H2: Skin conductance will be significantly higher when a knife threatens the virtual prosthesis compared to a period of time before the threat in both conditions
- H3: There will be a positive relationship between ownership and agency scores in both conditions.
- H4: Ownership scores will be significantly lower for the EMG control (prosthetic hand condition) than natural hand control (hand condition).
- H5: Agency scores will be significantly lower for the EMG control (prosthetic hand condition) than natural hand control (hand condition).
- H6: Embodiment scores will be significantly lower for EMG control (prosthetic hand condition) than natural hand control (hand condition).
- H7: Skin conductance will be significantly higher when a knife threatens the virtual prosthesis compared to a period of time before the threat in both conditions
- H8: There will be a positive relationship between ownership and skin conductance scores in both conditions.
- H9: Skin conductance scores will be significantly lower for the EMG control (prosthetic hand condition) than natural hand control (hand condition).
- H10: There will be a negative relationship between inaccuracy (amount of accuracy issues) and all embodiment scores and skin conductance in both conditions.
- H11: Those who have greater accuracy issues will have significantly lower embodiment scores and skin conductance in both conditions.

Based on comparisons between questionnaire subscale scores with respective control scores (see Figure 81), a subjective feeling of ownership, agency, and embodiment was found in both the prosthesis and hand conditions. This supports previous active movement VHI studies (e.g., Sanchez-Vives et al., 2010; Snow et al., 2017; Yuan & Steed, 2010) as well RHI studies including a passive sensory substitution (e.g., D'Alonzo & Cipriani, 2012; D'Alonzo et al., 2015). Supporting the hypothesis, there was also a positive relationship found between ownership and agency in both conditions (see Figures 94-95), suggesting that participants who experienced greater ownership also experienced greater sense of agency. This could either be due to circumstances during the experiment encouraging both subjective sensations, or that either the experience of one encouraged the experience of the other. This latter interpretation supports conclusions from Kalckert and Ehrsson's (2012) study, in that when the hand was experienced as part of the body, there was a stronger sense of agency. In addition, they found agency could be experienced over a rubber hand when this was

experienced as an external object. These findings might suggest a directional influence of ownership leading to agency, rather than the reverse.

In support of the hypothesis, a significantly greater feeling of ownership was found for the hand condition than prosthesis condition (see Figure 81). This could be interpreted as being due to controlling the virtual prostheses via an anatomical hand, which encourages a stronger feeling of ownership because of the natural control method of opening and closing the hand. Alternatively, or additionally, the difficulty in controlling the prosthesis and electrotechnical delay could reduce ownership. A further alternative or additional cause could be due to feed-forward predictions (Saunders & Vijayakumar, 2011) of finger movement providing a greater amount of information than simply flexing arm muscles.

A non-significant difference between conditions was found for agency, challenging the hypothesis. Whilst feed-forward predictions of individual finger movement might afford further sensory information to increase ownership, the feeling of agency could still be experienced in prosthetic hand condition. In addition, the natural vs unnatural control method might only significantly impact ownership rather than agency, which is more influenced by synchrony of movements. These suggestions might explain why there was no significant difference. However, the interpretation of synchronous movement of the prosthetic hand and virtual prosthesis leading to agency would seem to challenge the earlier suggestion of electromechanical delay impacting ownership. Unless such a delay selectively impacts each aspect of embodiment differently (i.e., the delay is enough to reduce ownership for some, but not enough to reduce sense of agency). The finding for agency is likely responsible for the overall embodiment not being significantly different between conditions. The non-significant difference found between the order of conditions for ownership, agency, and embodiment suggests that there was no order effect, for example having a stronger effect the 2<sup>nd</sup> time the experiment was run for the participant because of the familiarity. This finding, in addition, to the counterbalancing of conditions rules out the impact of order effects on findings.

For skin conductance responses, the finding of a significant difference between the highest value during the knife animation and the average value before the knife fell (see Table 23) suggests participants had a heightened emotional response to the knife. This was found for the prosthesis and hand conditions, suggesting that both forms of control method produced a physiological response. However, this might be due to a response to the knife in



general or the surprise of a sudden appearance of something falling near the area of attention, rather than being an indicator of hand ownership. Support for this interpretation potentially comes from the non-significant relationship between ownership scores and SCR scores, as this suggests that responses to the knife were not due to feeling ownership of the virtual prosthesis, instead implying alternative causes. Also, whilst ownership was stronger in the hand condition SCR scores were not significantly different between the prosthesis and hand conditions suggesting that SCR values were overall similar across conditions and greater ownership in one condition had no impact on this.

From responses participants provided to questions after the experiment, a large proportion were aware of the accuracy (see Table 26), with fingers moving incorrectly being the most noticeable, and fingers flickering to a lesser extent (see Table 27). Roughly one quarter of these participants felt the accuracy impacted on their experience (in terms of how they answered questions), with another quarter saying it had a little impact (see Table 28). It should be noted however, that the importance of this is constrained by the assumption that participants are aware of factors influencing their embodiment of the prosthesis. In terms of specific things noticeably influencing experience of the hand, only a limited amount of information was provided, with fingers flickering, moving incorrectly, and the delay between hand movement and virtual hand movement being mentioned by only one person each (see Table 29), suggesting these aspects were not particularly impactful for people in general or they, they were not consciously aware of them (but still had an impact), or they did not wish to report these factors having an impact for another reason.

A potential limitation of the study is that due to the design of the motion tracking rig participant's arms were not physically located in the same space for each condition. With anatomical hand control it was resting on the table, whereas for prosthesis hand control it was under the table resting on their legs. This could impact embodiment, either with their arm more closely matching the perceived height of the virtual arm, or the physical feeling of resting on a table more matching the virtual prosthesis in the hand control condition. There are two challenges to this. Firstly, the horizontal position of the arm relative to the virtual prosthesis was roughly matched in both conditions and aimed to be in close proximity to the virtual arm. This distance has been shown to impact body ownership in RHI studies (e.g., Kalckert & Ehrsson, 2014). Secondly, for most participants, the position of the hand being different between conditions did not matter (see Table 30), and for those which it did, this

more related to being harder to control the hand when under the table, or the impact from feeling the table below the hand in the hand condition (see Table 31, rather than the spatial difference having an impact).

A further potential limitation is that the knife animation may not be perceived as a threat and/or skin conductance. Notably, only half the participants felt the knife was either a threat or a little threat (see Table 32). For those who felt it was not a threat, the most reported reason was knowledge that either the knife or hand was not real, and that the knife did not seem realistic (see Table 33). Even fewer participants reported other aspects influencing response to the knife, such as the slowness or lack of sound from the knife. The question remains whether improvements to the knife (see Table 34) would impact on relationships with ownership (i.e., high ownership producing a strong response to the knife) and thus be reflected in differences in SCR between conditions (i.e., the hand condition having higher ownership and SCR than the prosthesis condition). A further psychological component might need to be explored. This is whether the perception of the virtual prosthesis being mechanical, rather than an anatomical limb, reduces response to the threat in terms of ownership (i.e., whether the limb feels part of the user has no significant bearing on a response to a threat to that limb). In addition, as previously mentioned, a SCR could simply be due to a response to the knife or startle response which was not explored in the study.

For the accuracy analysis there was no significant relationship between accuracy and ownership, agency, embodiment, or SCR scores in both the prosthesis and hand conditions (see Table 36). This possibly suggests that overall there may be no significant impact from accuracy on scores. However, looking at the direction of the relationships in the conditions may provide clues for potential impact (e.g., with some participants or a weak influence on participants overall). In the prosthesis condition, all except ownership were negative suggesting greater inaccuracy was related to lower scores. It is unclear why ownership displayed the opposite trend. Also, the hand condition displayed the opposite trend overall compared to the prosthesis condition, as in, all had a positive relationship except ownership.

One partial explanation is that if the issues with accuracy are reducing ownership this might be more salient in the hand condition. This would be because of the sensory feedback from the hand and finger position not matching the virtual hand, and thus disrupting ownership. This explains why the impact on ownership for the prosthesis condition might

differ, but not why this relationship was positive (i.e., greater accuracy issues associated with stronger ownership). Perhaps this relates to some aspect of how the prosthesis was controlled by some participants, which lead to stronger ownership, and greater accuracy issues (e.g. with the hand being moved more quickly or forcefully).

Accuracy issues particularly disrupting agency in the prosthesis condition could have occurred if the hand was particularly difficult to control for some participants, leading reduced agency and potential disruption to motion tracking. This does not explain why greater accuracy issues were associated with stronger agency in the hand condition, unless such issues lead to corrections in movement (i.e., bringing the virtual hand back to the correct position), or faster hand movement lead to stronger agency but disruptions in motion tracking. In both conditions, agency likely lead to the direction of relationships with embodiment due to higher agency scores thus having more impact on the embodiment score than ownership. Despite these suggestions, further to all correlations being non-significant they are very weak relationships so limited emphasis should be placed on these.

Further comparing between conditions, there was no significant difference overall in accuracy between the conditions (see Figure 104). This suggests that despite observable differences between conditions the impact on the overall level of accuracy was roughly the same for each condition. Despite the prosthesis condition overall having a larger total inaccuracy score, more participants specifically reported being aware of the level of accuracy in the hand condition (likely due to the sensory feedback, see Table 26). Also, out of those who felt the accuracy impacted their response to questions, a small number suggested this was more impactful in the hand condition, whereas none mentioned the prosthesis condition (see Table 28). However, focusing on specific categories of accuracy, the virtual hand being in an incorrect position was more prevalent in the hand condition whereas fingers flickering was more prevalent in the prosthesis condition (see Figure 104). These can be explained by participants having freedom of movement in the hand condition (despite being instructed to keep their hand in a certain location) which increased the risk of hand position inaccuracies. Also, flickering being more prevalent for the prosthesis is explainable by the Leap Motion device being designed to perceive human hands and its somewhat greater difficulty in accurately perceiving a prosthetic hand.

After removing those who had perceived accuracy issues as being a disruption, the results were the same (see Figure 105) which lends confidence in the original findings between conditions. Also, adding further confidence to accuracy issues not impacting results, there was still no significant relationship between accuracy and any scores. When comparing between low and high accuracy issues groups (based on objective accuracy), for the prosthesis accuracy groups, patterns were comparable except for embodiment score as there was a significant difference between conditions in the high accuracy issues group (see Figure 107), whereas there was no difference for the low accuracy issues group (see Figure 106). Similarly, when comparing between groups for the hand condition patterns were comparable except for embodiment score as there was a significant difference between conditions in the high accuracy issues group (see Figure 109) compared to the low accuracy issues group (see Figure 108).

Referring to mean embodiment scores for the separate groups, the significant embodiment difference for the high accuracy issues groups appears to relate to the hand condition embodiment for both. For the prosthesis high accuracy issues group, prosthesis embodiment was roughly equivalent to the low accuracy issues group. Thus, the cause being due to the hand embodiment adds support to accuracy not directly diminishing scores, at least for embodiment. Adding further weight to this, is the finding of the significant embodiment difference for hand high accuracy issues group being due to a higher embodiment score compared to the low accuracy issues group (i.e., embodiment was stronger despite the greater accuracy issues). Finally, the finding of all questionnaire measures and SCR not differing between high and low accuracy issues groups (see Figures 110-111) further suggests that any accuracy issues did not significantly impact responses to the experimental measures. This being found for both prosthesis and as hand accuracy conditions lends further confidence in accuracy issues having a limited impact on how participants responded to the experimental measures.

The findings of this study lead to various potential avenues to explore further. Suggestions for future research include testing with upper-limb prosthesis users. As control method may naturally disrupt embodiment for prosthesis users it would be useful to test this experimentally with the current or adapted set-up. This would have to involve unilateral limb-loss and compare between control of the virtual prosthesis with the myoelectric prosthesis and their intact limb. This would also allow for comparing levels of embodiment achieved

with prosthesis users with the intact individuals in the current study. Amputees and those with congenital limb absence might differ in embodiment of the prosthesis, and in comparison, to intact individuals. Having a previous hand which is then replaced through EMG control of a virtual prosthesis might make embodiment harder to achieve (i.e., less vivid) because of the difference in control, or easier due to having previously experienced a hand. However, compared to intact individuals both amputees and congenitals would provide a more authentic test of embodiment of the prosthesis in the EMG condition without having their hand present when flexing their muscles. In addition, this line of research could extend to comparing between further control methods, such as body-powered prostheses.

Another important area to explore would be to isolate the impact from control method and difficulty in controlling and delays with the prosthesis. One such approach would be to keep the control method constant (e.g., just EMG control) and systematically explore the impact of delays. As detailed earlier, myoelectric prostheses include a fixed delay and variability in response, introducing uncertainty over hand behaviour (Chadwell et al., 2016). Saunders and Vijayakumar (2011) also highlighted the importance of feed-forward models for functionality, and such models have also been identified as being important for the feeling of agency and body ownership (Kalckert & Ehrsson, 2012).

In addition to functionality, appearance of the prosthesis has also been found in research as a reason for users abandoning their prosthesis (Biddiss & Chau, 2007a, 2007b). Also, appearance of myoelectric prostheses has been reported by users to be of importance to their experience of their prosthesis (Wijk & Carlsson, 2015), and in terms of “not standing out” and appearing as “normal” as possible (Ritchie, Wiggins, & Sanford, 2011). As appearance has been raised as important for some prosthesis users, this could also be a factor influencing PE. Potential support for this is a virtual hand ownership study which found that moving a human looking virtual hand produced stronger feelings of ownership than an abstract looking hand (Argelaguet et al., 2016). The question remains whether a similar effect would be found between ownership of prostheses of varying appearances. For example, it would be useful to explore whether a virtual prosthesis more ‘natural’ in appearance influences the degree of ownership differently than one which appears more ‘robotic’. There may be an interaction between delay and appearance on ownership, and as Ritchie et al. (2011) argues, function and appearance should be considered together. Thus, the level of temporal synchrony between participants’ motor commands and virtual hand movement, and

the specific appearance of the virtual prosthesis could be altered to systematically measure their impact on PE.

In conclusion, overall findings for the experiment have been partly as expected, with an observable level of ownership, agency, and embodiment in both conditions, but some clear differences between them. There were some notable issues to do with both the accuracy of motion tracking and control of the prosthesis, however, further exploration suggested that accuracy issues may have only directly impacted some participants in terms of their conscious experience. Also, removing these participants still resulted in the overall patterns holding up. It is suggested that accuracy differences between conditions are not particularly impactful, but to inform future research these issues should be minimised to avoid the potential impact on some participant's experiences during the experiment. Development and testing of accuracy of motion tracking in this study could serve as useful guidance for future IVR studies exploring prosthetics. Overall, the experiments suggested a certain level of PE (notably with agency and to a lesser extent ownership) was achievable with the prosthetic limb but this was noticeably reduced compared to with anatomical hand control.

## Chapter 6: Discussion

At the start of the PhD it was determined from literature that there is large degree of complexity surrounding prosthesis embodiment (PE), involving a potentially complicated process of adapting to a prosthesis. It was identified that this process may be potentially impacted by several factors, but the full range of these factors was unknown. As highlighted by Murray (2004) there was a need to fully understand the range of factors to help inform the processes involved in encouraging PE during rehabilitation. However, the benefits of PE appeared to be largely assumed, along with the temporal nature and variability of PE being unclear. Therefore, our research questions centred on asking what factors influenced PE, what were the outcomes, how such experiences of the prosthesis changed over time and the ways in which the prosthesis could be experienced by users.

The qualitative study revealed that a prosthesis could be experienced in numerous ways with specific feelings potentially characterising additional aspects of PE. A much larger range of factors seemed to be associated with PE than previously anticipated, including both potential influences and outcomes of PE. It also revealed that outcomes could be both overall in nature (i.e., affecting the person or their use of the prosthesis in general) or temporary in nature (i.e., affecting the person for a short amount of time based on a specific event occurring). The temporal aspects of PE were revealed to manifest as both gradual changes over time and a temporary shift in PE. Thus, there were not only general influences of PE, but factors which influenced temporary fluctuations in PE.

As the qualitative study acted as a deep exploration into PE, the direct association between specific factors and PE, along with the broader prevalence in a larger population, were difficult to determine. Thus, the survey study asked such questions through developing the findings using quantitative data. This study highlighted that PE is not dichotomous but is experienced as varying gradients and that this related to a large number of factors that were suggested in the qualitative study. It also confirmed that the novel findings of motivational and social factors may play an important role for some users in terms of whether there is a desire for PE and the impact of social responses in relation to an altered body image. A number of factors seemed related to the control of the prosthesis and directly relevant for the sense of agency, whereas some others appeared more relevant for ownership. There was also

further support for the temporal nature of PE, where some users may experience a gradual change in PE and/or experiencing a temporary shift in their experience.

Whilst the statistical findings added further weight to the qualitative data it was acknowledged that correlational findings are limited in terms of identifying a causal relationship. This informed development of an experimental paradigm utilising Immersive Virtual Reality (IVR) in order to begin systematically testing specific factors associated with PE. This study found that a reduced sense of ownership was experienced through control of a virtual prosthesis using direct EMG-control of a myoelectric prosthesis, compared to natural anatomical hand control. However, sense of agency did not significantly differ between the conditions. The suggestion from findings is that control method of a prosthesis might impact and reduce a sense of ownership, but that a sense of agency is less likely to be disrupted. It also, found that whilst ownership was reduced compared to natural hand control, this was of a potential high enough level to allow for future studies to explore PE using the virtual-hand illusion (VHI) technique. This also supports previous active movement VHI studies (e.g., Sanchez-Vives et al., 2010; Snow et al., 2017; Yuan & Steed, 2010) as well rubber-hand illusion (RHI) studies including a passive sensory substitution (e.g., D'Alonzo & Cipriani, 2012; D'Alonzo et al., 2015), whilst providing new knowledge that a certain level of ownership and agency can be achieved using direct control of a motion-tracked myoelectric prosthesis. The study found ownership correlated with agency supporting the previously expected relationship between these variables (de Vignemont, 2007), and research suggesting that one might influence the other (e.g., Kalckert & Ehrsson, 2012). However, unexpectedly, embodiment did not correlate with skin conductance, which has previously acted as a proxy for ownership.

## **6.1 Novel contribution from the thesis**

One novel contribution of the thesis has been identifying that beyond use of a prosthesis there are many other factors which appear to influence the presence or absence of PE. A greater range of experiences which may highlight aspects of PE (such as having an emotional connection) have been revealed which may be useful to explore in future studies of PE and further consider their importance as a proxy for or direct measure of PE. The thesis has also highlighted the temporal nature of PE, in particular with the temporary fluctuations of PE and potential individual differences relevant for this. Overall, the individual nature of



PE raises important questions for rehabilitation, not only in considering what factors might encourage PE but also in whether the user wishes to experience PE. The motivational component which emerged as an important new finding further emphasises the individual nature of PE and specifically with what the user desires or expects from their prosthesis. This may have broad implications for the user, such as type of limb absence or type of prosthesis, but also individual aspects specific to the person. Another aspect raised by the thesis is that due to there being a larger range of outcomes than previously considered, some of these correspond to influences. For example, proficiency with the prosthesis. This has implications for studies which specifically only considers such variables as an influence or an outcome. In some cases, whether the factor is an influence or an outcome may be misidentified, in other cases it may truly act as both as both an influence and outcome for the user. One further novel contribution is the identification of negative outcomes of PE. It was previously assumed such outcomes would be positive, hence the suggestion of encouraging PE during rehabilitation. Whilst many positive elements of PE were reported, some negative aspect appear to be relevant, such as the user feeling incomplete without their prosthesis and feeling negative affect when the prosthesis is broken, potentially due to feelings being projected from the prosthesis towards themselves or their body.

## **6.2 Limitations of the research studies**

The studies detailed in this thesis had some limitations which will be discussed in turn, and in consideration of how they might impact its findings.

### **6.2.1 Qualitative study limitations.**

For the qualitative study this was limited by relying on self-report of experiences, being conducted via email interviews, having a limited sample size and generalisations to the wider population of prosthesis users therefore being difficult. Firstly, through discussing prosthesis user's experiences across the life of their prosthesis, there is the assumption that at face value they are correct in their memories, feelings, and speculations. Of note, where participants declared they were unsure of something this was coded as being unsure, however, there is still the risk of information provided being incorrect. In addition, they were being asked things about their prosthesis which they might not have considered before or become confused with the question, adding to this risk. Thankfully, some participants did declare when they were unsure about a question and in these cases, it was clarified further to

ensure they understood, or if it was identified after the interview that there might have been confusion (e.g., contradiction) this was coded as unclear.

Whilst the use of email interviews allowed participants time to consider responses (hopefully to protect against the issue of being confused, as mentioned above) this only allowed participants to be those who had access to emailing. Thus, this could have slightly biased the sample to those with access and ability to type. Despite this, the recruitment method of identifying participants through online sources (e.g., social media, websites, forums) implies that such participants were able to gain access to online material and in the case of social media or forums, also potentially willing to discuss their experiences. By its essence of being an email interview, this does not include some potential information which would be gained in face-to-face interviews, such as body language and small expressions, along with a dialogue developing more fluidly between the interview and participant. However, such aspects were considered as less vital for this specific study and non-verbal information less important than it might be for other qualitative methods.

By its nature, qualitative studies often have small samples, as this study did. Hence the study is limited by the number of participants. The experience of PE and factors associated with it was found to be somewhat variable, potentially due to memory issues or the individual awareness of certain factors (e.g. whether feelings changed gradually over time). Thus, the small sample size might not accurately capture all of the potential individual differences involved in PE. In addition, factors potentially associated with PE were only endorsed as being relevant by some of the participants, making the prevalence of each factor even more difficult to estimate. Due to these potential limitations, by having a small sample it is difficult to generalise these findings to the wider upper-limb prosthetics population. The survey study aimed to address this.

### **6.2.2 Survey study limitations.**

Whilst the survey studied aimed for a larger sample size to face some of the limitations posed by the qualitative study, the sample size was still limited (despite the recruitment strategy involving contacting a large number of global sources to request advertisement). Unfortunately, this resulted in a relatively small response rate. This possibly suggests that NHS ethical approval would have been beneficial in raising the sample size.

The target population of upper-limb prosthesis users are notably more difficult to recruit than lower-limb users due to the much smaller prevalence, but a larger sample was originally desired. It is possible some of the relationships explored with this fairly small sample were not large enough to gain an accurate view of significant differences or relationships, meaning some caution should be applied to overly interpreting these.

Through the design of an online questionnaire, the study was limited to those who have access to this, as with the qualitative study. However, other previous online questionnaires provided to upper-limb prosthesis users were explored to consider that this was appropriate. The study was also limited in terms of not including all the factors identified during the qualitative study, for practical purposes. A more overall limitation, however, is the inability to determine causality from the correlational data, making some interpretation of relationships challenging. This was navigated by particularly considering this limitation in my analysis and discussion when such factors could be considered as either an influence or an outcome.

### **6.2.3 VR study limitations.**

A potential limitation of the VR study is that due to the design of the motion tracking setup, participant's arms were not physically located in the same space for both conditions. With anatomical hand control it was resting on the table, whereas for prosthesis hand control it was under the table resting on their legs. This could have impacted embodiment of the virtual prosthesis, either with their arm more closely matching the perceived height of the virtual arm, or the physical feeling of resting on a table being congruent with the virtual prosthesis in the hand control condition. However, the horizontal position of the participant's arm relative to the virtual prosthesis was roughly matched in both conditions, thus aiming to be in close proximity to the virtual arm. In addition, most participants reported that the position of the hand being different between conditions did not matter. For those for which it did matter, they more related the difficult of controlling the hand when under the table, or the impact from feeling the table below the hand in the hand condition, rather than the spatial difference having an impact. This suggests there was limited impact but also how exactly this may have influenced the findings.

A further potential limitation is that the knife animation may have not been perceived as a threat by some participants. Notably, only half the participants felt the knife was either a threat or a little threat. Whilst physiological response is automatic and not consciously influenced, the skin conductance findings could have been impacted if the knife was perceived unconsciously as a non-threatening object presented to the hand. For those who felt it was not a threat, the most reported reason was knowledge that either the knife or hand was not real, or that the knife did not seem realistic. A very limited number of participants reported other aspects influencing response to the knife, such as the slowness or lack of sound from the knife. Despite this, there was an observable response to the knife across the sample, suggesting that it could have been seen as a threat, but there is a chance that the skin conductance response is due to a startle response rather than being perceived as a threat to the hand. It is unclear how much this may have impacted findings but the fact that there was no relationship between skin conductance and ownership in both conditions, suggests this risk has not impacted on the overall differences found between conditions.

In addition, interpretation of the findings of the control method influencing feelings of ownership is limited due to it conflating multiple possible factors. These include the impact of control via muscle flexes vs. anatomical hand movement, the difficulty or discomfort in controlling the myoelectric prosthesis, and/or any impact from the electromechanical delay or reliability of the prosthesis responding. A more general limitation relates to the use of non-prosthesis users experiencing and controlling a virtual prosthesis. This means extrapolating findings for the community of prosthesis users' needs to have some level of caution applied. For example, when flexing their muscles to control the prosthesis participants still felt their hand in a fist shape moving, as this was not locked in place. This may have impacted response to the virtual prosthesis (e.g., feeling their fist in a different position than the virtual hand and fingers).

### **6.3 Recommendations for future research**

The findings of the 3 studies point towards suggested future areas of research of interest/importance. The complexity of PE and factors associated with its presence or absence, including both influences and outcomes, suggests the next logical step to take after identifying the range of factors potentially associated with PE. See Table 38 for the list of

factors explored across the thesis, split by whether they were significantly related to PE or not.

Table 38

*Factors predicted to be associated with PE – split by significance*

Factors significantly related with PE	Factors not significantly related with PE
Feelings related to PE	Feelings related to PE
Emotional connection	
Feeling indispensable	
Feeling foreign	
Feeling like glasses analogy	
Temporal nature of PE	Temporal nature of PE
	Gradual changes
	Temporary changes
Factors associated with PE	Factors associated with PE
Amount of prosthesis use	Age of first use
Phantom limb pain	Length of time with prosthesis
Desire for prosthesis to feel part of the user	Type of prosthesis
Positive mindset	Type of limb absence
Body image	Phantom limb sensation
Benefits the prosthesis provides	Phantom limb position
Naturalness of control method	Personal customisation of prosthesis
Sensory feedback	Number of changes to prosthesis
Awareness	Negative attention
Planning tasks in advance	Satisfaction with appearance
Proficiency with prosthesis	Satisfaction with robustness
Satisfaction with functionality	
Satisfaction with fitting	
Satisfaction with comfort/weight	
Satisfaction with reliability	
Satisfaction with response speed	
Satisfaction with noise	
Satisfaction with prosthesis overall	

This should involve research identifying how such factors of influence interact with each other and contribute towards the extent a person experiences PE. Similarly, how outcomes of PE potentially interact and influence each other would be beneficial to understand which are influenced the most by PE, and whether such relationships are direct or due to other others afforded by embodiment of the prosthesis. It is suggested that a Grounded Theory (GT) would be useful for exploring these questions. A recently published study

developed GT in relation to sensory feedback and PE (Graczyk et al., 2019), however an over-arching theory exploring the complex interactions of factors associated with PE would be useful and develop further from this.

This line of research being proposed could also further delve into the individual differences aspect of these factors, as suggested at numerous points in the discussion. This could identify two aspects of individual differences: the factors which contribute towards PE for the majority of prosthesis users, and those which are more variable in their influence (i.e., whether the presence of a specific factor contributes towards an individual's PE or not). Secondly it could identify the relative importance of such factors for individuals. This was hinted at in the qualitative study where participants discussed contribution of specific factors for their PE or lack of PE (i.e., the most important factors for their experience). Thirdly, individual differences in the relative importance of PE could be explored further to understand whether desire for embodiment encourages PE, as suggested in the survey study and consider the importance of developing experimental or exploratory techniques to induce PE in upper-limb prosthesis users.

The suggestion of exploring techniques to encourage PE was touched upon in the literature review. Christ and Reiner (2014) highlighted possible applications of a RHI combined with IVR for rehabilitation. One such area could be to attempt to encourage PE. Current research applying RHI techniques directly to prostheses would require a specially adapted prosthesis, possibly only suitable for certain types and only usable by those who have access to such an expensive device. Thus, exploring the use of such techniques in IVR could be beneficial in providing an alternative, more flexible method, potentially useful for any prosthesis type. The suggestion here is to apply such techniques as a form of therapy or intervention, similar to how mirror-box therapy has been implemented into IVR. There is an increasing recognition of the benefits VR can provide for rehabilitation (e.g., Bohil, Alicea, & Biocca, 2011; De Mauro, 2011; Holden, 2005; Sveistrup, 2004; Wilson, Foreman, & Stanton, 1997) which supports this suggestion. However, the intervention approach would need to first develop a robust protocol, with PE measured in an experimental context. Then, it would need to explore 'carry-over' effects from the VR-protocol to a user's experience of their prosthesis outside of the context of the IVR system, in the same way as having to measure the persistence of PLP reduction over time. This approach, however, is constrained by requiring a

large sample and longitudinal testing of the effectiveness of the techniques for encouraging PE in a user's own prosthesis and how stable the change in PE would be.

The use of body ownership techniques applied to prosthetics in VR could also be applied to further exploration of factors that naturally influence PE using a VR prosthesis simulation, as the control method was explored in this study. It is suggested that the setup from the VR study is tested with upper-limb prosthesis users which could enable comparing between control of the virtual prosthesis with the myoelectric prosthesis and their intact limb, for unilateral prosthesis users. This would also allow for comparing level of embodiment achieved between prosthesis users and the non-prosthesis users currently tested. In addition, the area of research could be extended to compare between further control methods, such as body powered prostheses. Further testing could also explore the questions raised around response to a threat to the prosthesis.

Another important area to explore would be to isolate the impacts from control method and difficulty/discomfort in controlling the prosthesis, and delays/reliability with the prosthesis. One such approach would be to keep the control method constant (e.g., just EMG control) and systematically explore the impact of delays. As detailed earlier, myoelectric prostheses include a fixed delay and variability in response, introducing uncertainty over hand behaviour (Chadwell et al., 2016), which is important for the feeling of agency and body ownership (Kalckert & Ehrsson, 2012). In addition to functionality, as detailed previously, appearance of the prosthesis has been noted by users as important and a potential influence of rejection (e.g., Biddiss & Chau, 2007a, 2007b; Ritchie et al., 2011; Wijk & Carlsson, 2015). The question remains whether ownership would differ between prostheses of varying appearances. For example, it would be useful to explore whether a virtual prosthesis more 'natural' in appearance influences the degree of ownership differently than one which appears more 'robotic'. There may be an interaction between delay and appearance on ownership. Thus, the level of temporal synchrony between participants' motor commands and virtual hand movement, and the specific appearance of the virtual prosthesis could be altered to systematically measure their impact on PE.

## 6.4 Conclusions

In conclusion, the development of PE in a group of upper limb prosthesis users (both amputees and congenitals) has been identified as consisting of numerous aspects, involving both subjective feelings and bodily aspects processed unconsciously by the brain, such as the prosthesis becoming incorporated into the body schema. Relating to this, a large range of potential specific influences on whether PE emerges or the extent to which it does for an individual have been revealed, categorised and grouped, along with the potential outcomes of experiencing embodiment. The former is important for understanding the likelihood of the emergence of PE and the latter for understanding the positive benefits and potential negative aspects of PE for the user. In addition, unexpected knowledge of how embodiment can fluctuate over time has been gained which can aid understanding of the stability of PE or how this might develop. The potential of exploring factors associated with PE through controlled experimental conditions was begun with an IVR system. The impact of the control method, along with the latency and accuracy of the IVR system, was systematically tested. This suggested that the ownership of myoelectric prostheses could be influenced by the type of prosthesis, or more specifically the method of control.

Overall, implications of all the studies completed for this thesis are that through developing systematic understanding of how PE can vary and the numerous factors which appear related to this, rehabilitation services and prosthetics manufacturers and technicians can potentially be better informed. They can utilise the possible and likely influence of specific personal (e.g., phantom limb sensations), situational (e.g., amount of use of prosthesis), and design (natural control of the prosthesis) factors influencing PE so as to improve their designs and procedures. The findings also suggest that there is a desire for embodiment overall, and that important benefits may be afforded a user if they experience PE. Further understanding on the relationships between such factors is now considered the next step, along with experimental testing of specific factors.



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## Appendix A: Participant details for qualitative study

Table A1

*Details of participants for qualitative study*

	P1	P2		P3		P4	P5	P6	P7	P8	P10	P11
Gender	M	F		F		M	M	M	M	F	M	F
Age	51	26		25		49	73	44	45	29	47	57
Country	N.Ireland	Canada		USA		Switz	UK	UK	USA	UK	USA	USA
Limb absence side	R	R	L	R	L	R	L	L	L	R	R	R
Amputation or congenital	A	C		C		A	C		A	A	A	A
Amputation cause	T					D			T	T	T	T
Level of limb absence	B E	B	B	B	B	B E	B	B E	B E	A	A E	A E
Before amputation hand dominance	L					R			R	R	R	R
Which limbs have received a prosthesis	R	R	L	R	L	R	L	L	L	R	R	R
How many years have you been using your prosthesis	43	1	1	22	22	8	67	42	26	1	1	2
Years between limb loss and first prosthesis	1	1	1	3	3	1	6	2	*	1	1	1
Type of prosthesis	<b>CO</b> , M	B	B	M	M	<b>CO</b> , M, <b>B</b>	C	<b>CO</b> , M, <b>B</b>	B	B	M, <b>B</b> **	M

*Note:* R = right; L = left; A = amputation; C = congenital; T = trauma; D = disease; BE = below elbow; AE = above elbow; CO = cosmetic; M = myoelectric; B = body-powered; Bold letter = most used prosthesis

\*not mentioned

\*\*most used not indicated

## Appendix B: Sources contacted for qualitative study

Table B1

*Sources contacted to advertise the qualitative study and outcomes*

	Replied	Supported	Social media	Forum	Website news	Newsletter	Magazine
Associations/charities							
Limbless Association	No				Yes		
Limb Power	Yes	Yes					
Port-er	Yes	Yes	Yes		Yes		
Finding Your Feet	Yes	Yes	Yes		Yes	Yes	
Douglas Bader Foundation	Yes	Yes	Yes	Yes	Yes		
Blesma	No						
Limbcare	Yes	Yes					
Amplitude	Yes	Yes	Yes		Yes	Yes	Yes
Amputee.ie	No						
Amptraide	N/A						
ADEPA	N/A						
BMAB	N/A						
KMK	N/A						
Momentum	N/A						
Amputee Coalition	Yes	Yes	Yes		Yes		
Limbs 4 Life	Yes	Yes	Yes				
Amputees Amplified	Yes	Yes			Yes		
Amputee Coalition of Canada	Yes	Yes	Yes				
Abled Amputees of America	No						
Limbs for Life Foundation	Yes	Yes	Yes				
The War Amps	No						
Enabling the Future	No						
Bespoken	No						
Alternative Limb Project	No						
Aussie Hands Foundation	Yes	No					
Amputee News	No						
Reach Out Magazine	No						
Stumps R Us	No						
Amputee Association of New South Wales	No						
Arms Within Reach	No						
Ableize	No						
Able Here	No						
Disabled World	No						
Prosthetic Ink	No						
Disabilities-R-Us	No						
Scope	Yes	Yes		Yes			
RESNA	No						
Disability Horizons	Yes	Yes	Yes				
Disability Link	No						
Disability Today	Yes	Yes	Yes		Yes		

Disability News Services	Yes	No					
Disability Today Network	No						
Able Magazine	No						
Canadian Centre on Disability Studies	No						
World Institute on Disability	No						
Centre for Disability Studies (University of Leeds)	No						
Centre for Disability Studies (Sydney)	No						
New England Amputee Association	No						
Society for Disability Studies	Yes	Yes					
Tasmanian Amputee Society	Yes	Yes	Yes				
AFSG	Yes	Yes	Yes				
ARATA							
NCHPAD	No						
Institute on Disability	No						
National Amputee Foundation	No						
Artlimb	No						
Amputee Federation of New Zealand	Yes	Yes	Yes			Yes	
Rebekah Marine	No						
Ottobock	No						
Ottobock UK	No						
Ottobock US	No						
Touch Bionics	No						
Midland Association for Amputees and Friends	No						
Prosthetics in Motion	No						
Mending Limbs	No						
TRS Prosthetics	No						
Dianceht	Yes	Yes	Yes				
OPAF	No						
AOPA	Yes	Yes	Yes				
Ossur	No						
AOPA (Australian)	Yes	Yes	Yes				
AAOP	No						
Specific Forums/Email Discussion Lists							
OANDP-L	Yes	Yes	Yes		Yes	Yes	Yes
AMP-L Listserv	Yes	Yes		Yes			
Amputee Support Group	Yes	No					
Reddit Amputee Forum	Yes	Yes		Yes			
Reddit Prosthetics Forum	Yes	Yes		Yes			
The Open Prosthetics Project	Yes	Yes		Yes			
Ampower	No						
The Amputee Discussion and Support Forum		Yes		Yes			
Heather Mills	No						
Arm-Amp Listserv	No						
Health Boards Amputation (Prosthetic sub-forum)	Yes	No					
Amputee Forum	Yes	Yes		Yes			
Daily Strength	Yes	Yes		Yes			
Just social media pages (not social media linked from associations/forums/clinics)							
Scottish Amputees	Yes	Yes	Yes				
United Amputee Community Charity	No						
Limb Loss Alliance	No						

Peer Support 4 Amputees

No

*Note: Supported* = said they would be happy to support the research or I noticed they posted the advert.

N/A = Sources who were asked on behalf of another source to post and did not have direct contact with me.

## **Appendix C: Introductory email, advertisements and online poster for qualitative study**

### **C.1 Introductory email to send to sources**

#### **New source email to send (study live)**

Subject line -

Request to advertise PhD research (University of Salford) study

School of Health Sciences  
Allerton Building,  
University of Salford,  
Salford,  
Manchester,  
M6 6PU

/07/16

Dear,

My name is Andrew Hodrien and I am a PhD researcher from the School of Health Sciences at the University of Salford (Manchester, UK) conducting research on ‘prosthesis embodiment’ for upper limb amputees or congenital amputees. The title of the project is ‘A Content Analysis of factors associated with embodiment of a prosthetic upper limb’.

The aim of this study is to identify a range of factors which are associated with upper limb prosthesis embodiment (i.e., a prosthetic limb is experienced as ‘part of’ the user) with the purpose of understanding the factors involved in why some prosthesis users feel like their limb is a part of their body, whilst others do not. We hope that ultimately this knowledge may benefit strategies for rehabilitation.

The research will involve semi-structured interviews through email which will be confidential. They will be asked to describe their experiences with their prosthesis along with providing some background information. This study has been assessed by the University of Salford’s ethics committee and follows the research code of The British Psychological Society.

I would like to please request permission for you to post a small advertisement of the study on my behalf to your readers on.....which may be of interest to them. Also, if there is anywhere else suitable you would be happy to post it to. Please see the attached advert to post which includes a link to a University webpage with further information on the study and contact details for interested participants.

I have been asked to keep a record of when the advertisement gets posted and where to, so could you please confirm once you have posted it (if happy to do that) and let me know where it gets posted?

Many thanks in advance.

Yours sincerely/faithfully,

Andrew Hodrien

## C.2 Advertisement for qualitative study

### **Have you been using an upper limb prosthesis? - Research participation request**

If so, we are interested to hear from you about your experiences of this and participate in research from the University of Salford – ‘*A Content Analysis of factors associated with embodiment of upper limb prostheses*’.

We would like to hear from you if your use of a prosthetic limb is due to either amputation or congenital limb absence as long as you have spent some time using a prosthesis.

Please follow this link to a University webpage detailing more information on the research and how to participate or enquire further about the study. **Recruitment from 1<sup>st</sup> June to 18<sup>th</sup> September 2016 -**

<http://goo.gl/DRnuSy>

Many thanks,

Andrew Hodrien (PhD researcher)

## C.3 Twitter advertisement for qualitative study

Have you been using an upper limb prosthesis? Please see Andrew Hodrien's PhD research (University of Salford) - <http://goo.gl/DRnuSy>

#### C.4 Online poster for qualitative study



### Project title – ‘A Content Analysis of factors associated with embodiment of upper limb prostheses’.

#### Do you use or own any form of upper-limb prosthesis?



We are interested to hear from you about your experiences of prosthesis use and if either your use of a prosthetic limb is due to amputation or congenital limb absence as long as you have spent some time using a prosthesis.

#### **Study aim**

The aim of this study is to identify a range of factors associated with upper limb prosthetic embodiment (the feeling of the prosthesis being part of you).

#### **What the research will involve -**

The researcher will conduct an interview with you through email which will be confidential.

Please click [here](#) for a full participant information sheet with full study details and then contact the researcher to express your interest.

Andrew Hodrien (PhD researcher) – [a.d.hodrien@edu.salford.ac.uk](mailto:a.d.hodrien@edu.salford.ac.uk)

Main supervisor – Adam Galpin ([a.j.galpin@salford.ac.uk](mailto:a.j.galpin@salford.ac.uk), Tel: 0161 295 7146)



## Appendix D: Interview schedule and background information form for qualitative study

### D.1 Interview schedule

- 1) Please can you describe your relationship with your prosthesis (e.g., How do you view or feel about your prosthesis)? Please provide as much detail as you are happy/able to share.
- 2) Can you think of any reasons why you feel this way about your prosthesis?
- 3) In what ways do you feel differently about your prosthesis from your intact limbs / other arm?
- 4) Do you feel the length of time you have had your prosthesis has influenced how much it feels part of you?
- 5) Have you found that a greater use of your prosthesis changes this feeling?
- 6) Have there ever been any times when it has felt more like a part of you? What were you doing? Why do you think that was?
- 7) Do you think the type of prosthesis you have relates to whether you feel it is part of you?
- 8) Do you think how satisfied you are with your prosthesis (e.g., with its look or functionality) may have influenced this feeling?
- 9) Have you had an experience of your limb still being present (known as phantom limb sensations)? If so, can you please describe how it feels and where it is in relation to the prosthesis?
- 10) **(If they have a phantom limb)** Do you feel your phantom limb influences how much the prosthesis feels part of you?

- 11) **(If they have a phantom limb)** Do you have pain from your phantom limb and do you feel this influences how much the prosthesis feels part of you?
- 12) Do you feel your amount of sensory feedback influences how much the prosthesis feels part of you?
- 13) Could you please describe how much this feeling has changed over time (if it has)?
- 14) Do your feelings towards your prosthesis (i.e., whether you feel your prosthesis is part of you) have any particular outcomes for you?
- 15) Have you used or do you think you would use your prosthesis more if it felt part of your body?
- 16) Can you or do you think you could perform any activities better as a result of this feeling?
- 17) Has your awareness of your prosthesis changed over time?
- 18) Do you feel this awareness relates to whether you feel your prosthesis is part of you?
- 19) Did how you feel about your body before using the prosthesis (e.g., how positive or negative you felt about how it looks) influence how much you felt the prosthesis was part of you?
- 20) Does how much you feel your prosthesis is part of you influence your feelings towards your body (e.g., how positive or negative you feel about how it looks)?

## D.2 Background questions/demographic information

### A Content Analysis of factors associated with embodiment of upper limb prostheses

Please fill in the information in the following table, but questions are voluntary so you do not have to answer any question you do not wish to. Some questions are tick boxes – please double click in the box then change the ‘Default value’ to ‘Checked’ and click OK (if you make a mistake you can change it to ‘Not checked’). Some other questions are for you to fill in so please write the relevant information. Once completed, please save and email it back to the researcher.

---

1) Gender	Male	Female
	<input type="checkbox"/>	<input type="checkbox"/>
2) Age	Please write:	
3) Country of residence	Please write:	
4) Which side(s) is/are affected by limb absence?	Right	Left
	<input type="checkbox"/>	<input type="checkbox"/>
5) Do you have limb loss as a result of a limb amputation or were you born without one or more limbs (congenital limb absence)?	Amputation	Amputation
	<input type="checkbox"/>	<input type="checkbox"/>
	Congenital limb absence <input type="checkbox"/>	Congenital limb absence <input type="checkbox"/>
	Trauma <input type="checkbox"/>	Trauma <input type="checkbox"/>

6) If prosthesis use is due to amputation what caused the amputation (e.g., trauma, disease)?

Disease

Disease

Other

Other

N/A

N/A

7) What level of amputation/congenital limb absence do you have?

Hand

Hand

Below elbow

Below elbow

Above elbow

Above elbow

Shoulder

Shoulder

8) If you lost a limb through amputation, were you left or right handed beforehand?

Left-handed

Right-handed

N/A

9) For which upper limb(s) have you received a prosthesis?

**Right Arm**

**Left Arm**

10) How many years (if less than one year please write one) have you been using your prosthesis for? (if you have

Please write:

Please write:

more than one device, please answer questions 10 and 11 for the one you use most often)

11) How many years (if less than one year please write one) was it until you started using your prosthesis (since amputation/born with limb absence)?

Please write:

Please write:

12) What type of upper limb prosthesis do you use (please tick all that apply and highlight the name in bold for the one you use most often)?

Cosmetic

Cosmetic

Myoelectric

Myoelectric

Body-powered

Body-powered

## **Appendix E: Coding Manual for qualitative study**

A Content Analysis of factors associated with embodiment of upper limb prostheses

### **Instructions**

- 1) Read the coding manual to familiarise yourself with the structure and content.
- 2) Read the interview transcript twice to familiarise yourself with the interview overall.  
Code the interview transcripts in the spreadsheet following this manual.
- 3) Code the interview transcripts in the Excel spreadsheet following this manual.
- 4) In interviews ‘I:’ represents interviewer dialogue and ‘P:’ represents participant dialogue. For just the participant dialogue, highlight the relevant text in the interview then add a comment as track changes. In the comment write the sub-section descriptor followed by a dash and then the code label (codes are in bold in the manual), for example: “Feelings – Overall feeling towards prosthesis”, “Factors influencing – Length of time with prosthesis”. If the same segment of text belongs to multiple codes highlight the text again to add a separate comment/code e.g., if discussing where their feelings changed temporarily this would be coded in both the ‘Factors influencing temporary feelings towards prosthesis’ section and the ‘Feelings towards prosthesis’ section (feeling changing over time).
- 5) If you spot discrepancies or corrections needed alter this manual accordingly (e.g., if a previous factor description or coding numbers needs changing, or a new factor needs to be added). Notes can also be added to the spreadsheet at the end of each row (for a participant) or below a column if comment relates to a factor in general.

### **Coding manual structure**

Factors of interest are split across 5 sub-sections for descriptive and analytical purposes (start of a new section in the spreadsheet is highlighted in purple). Label in brackets is the short hand description to use for codes (see note number 4 above for examples):

- 1) **Feelings towards prosthesis (Feelings)**
- 2) **Factors influencing feelings towards prosthesis (Factors influencing)**
- 3) **Factors influencing temporary feelings towards prosthesis (Factors influencing temporary)**
- 4) **Overall outcomes of feelings towards prosthesis (Overall outcomes)**
- 5) **Temporary outcomes of feelings towards prosthesis (Temporary outcomes)**

**Note:** For all following codes, where there is doubt over the relevant factor code as one of the following in the Excel spreadsheet: *Unsure* includes when the interviewee is unsure about the specific factor. *Unclear* includes when it is unclear how the factor should be coded (no need to code the interview text) or where there is no mention of the factor in the interview.

9. Unsure

10. Unclear

### **Feelings towards prosthesis**

**Note:** Feelings towards prosthesis include descriptions of how a prosthesis feels in relation to a user's body or self, whether such feelings have changed over time or temporarily, and whether there is a desire or need for the prosthesis to feel part of them. Such feelings could be described on their own or in relation to a specific factor (either as an influence or outcome). **For the beginning of the code use 'Feelings – ', followed by the relevant code below (factor name in bold).**

**Overall feeling towards prosthesis.** *Part of them* includes when the person describes their prosthesis as a part of them, part of their body or incorporated into them, they feel ownership over it, feeling part of their self. *Only as a tool and not part of them* includes describing their prosthesis as just a tool, not part of them, not part of their body or not incorporated into them, a lack of ownership over it, not feeling part of their self. *As part of them and a tool* includes any of the *part of them* descriptors along with feeling as a tool.

1. Part of them
2. Only as a tool and not part of them
3. As part of them and a tool

**Emotional connection with prosthesis.** *No emotional connection* includes when the person describes having no emotional connection with their prosthesis. *Emotional connection* includes when the person describes having an emotional connection with their prosthesis.

0. No emotional connection

1. Emotional connection

**Feels natural/not foreign.** *Feels unnatural/foreign* includes when the person describes their prosthesis as feeling unnatural or as a foreign (or similar word e.g., external alien) object. *Feels natural/not foreign* includes when the person describes their prosthesis as feeling natural or as an object which does not feel foreign to them.

0. Feels unnatural/foreign

1. Feels natural/not foreign

**Integrated into body image.** *Not integrated into body image* includes when the person describes their prosthesis as not feeling part of their physical body. *Integrated into body image* includes when the person describes their prosthesis as feeling part of their physical body.

0. Not integrated into body image

1. Integrated into body image

**Integrated into self.** *Not integrated into self* includes when the person describes their prosthesis as not feeling part of either their self. *Integrated into self* includes when the person describes their prosthesis as feeling part of either their self.

0. Not integrated into self

1. Integrated into self

**Wearing shoes/glasses/backpack analogy.** *Not like wearing shoes/glasses/backpack* includes when the person describes their prosthesis as not feeling like an external object they are simply wearing e.g., shoes, glasses, a backpack, or similar object. *Like wearing shoes/glasses/backpack* includes when the person describes their prosthesis as not feeling like an external object they are simply wearing e.g., shoes, glasses, a backpack, or similar object.

0. Not like wearing shoes/glasses/backpack

1. Like wearing shoes/glasses/backpack



**Expendable.** *Not expendable/Is indispensable* includes when the person says they would miss their prosthesis or feel incomplete without it (beyond the practical benefits it provides) if they had to be without their prosthesis. *Expendable/Dispensable* includes when the person says they would miss their prosthesis or feel incomplete without it (beyond the practical benefits it provides) if they had to be without their prosthesis.

- 0. Not expendable/Is indispensable
- 1. Expendable/Dispensable

**Feelings towards prosthesis change gradually over time.** *Feelings have remained the same* includes when the person says their current feelings are the same as they always remember having previously, feelings have remained relatively stable. *Feelings have changed over time* includes when feelings have noticeably changed gradually or rapidly.

- 0. Feelings have remained the same
- 1. Feelings have changed over time

**Feelings towards prosthesis change temporarily.** *Feelings have not changed temporarily* includes when the person says their current feelings are the same as they always remember having, feelings have remained relatively stable, feelings have changed over time. *Feelings have changed temporarily* includes when there has been a temporary change in feeling caused by some event.

- 0. Feelings have not changed temporarily
- 1. Feelings have changed temporarily

**Desire or need for their prosthesis to feel part of them.** *No desire or need for the prosthesis to feel part of them* includes when the person says they have no desire or need for their prosthesis to feel part of them, it is not important for them. *Desire or need for the prosthesis to feel part of them* includes when the person says they have a desire or need for their prosthesis to feel part of them, it is important to them.

- 0. No desire or need for the prosthesis to feel part of them
- 1. Desire or need for the prosthesis to feel part of them

## **Factors influencing feelings towards prosthesis**

**Note:** Factors influencing feelings towards prosthesis are where a specific factor is believed to influence (or not influence) the person's overall feelings towards their prosthesis (i.e., whether it feels part of them or not). An influence can include either encouraging or discouraging embodiment. **For the beginning of the code use 'Factors influencing –', followed by the relevant code below (factor name in bold).**

**Being born without arm(s).** *No influence* includes when the person feels them being born without their arm(s) has not had an influence on their feelings towards their prosthesis. *Influence* includes when the person feels them being born without their arm(s) has had an influence on their feelings towards their prosthesis. *Not applicable* includes when the person is an amputee.

0. No influence
1. Influence
2. Not applicable

**Being born with arm(s).** *No influence* includes when the person feels them being born with their arm(s) has not had an influence on their feelings towards their prosthesis. *Influence* includes when the person feels them being born with their arm(s) has had an influence on their feelings towards their prosthesis. *Not applicable* includes when the person has congenital limb absence.

0. No influence
1. Influence
2. Not applicable

**Length of time with prosthesis.** *No influence* includes when the person feels how long they have had their prosthesis for has not had an influence on their feelings towards it. *Influence* includes when the person feels how long they have had their prosthesis for has had an influence on their feelings towards it.

0. No influence
1. Influence

**Age of first use of prosthesis.** *No influence* includes when the person feels how old they were when they first starting to use their prosthesis has not had an influence on their feelings towards it. *Influence* includes when the person feels their age (e.g., as a child or teenager) when they first started to use their prosthesis has had an influence on their feelings towards it.

0. No influence

1. Influence

**Amount of use of prosthesis.** *No influence* includes when the person feels how much they have used their prosthesis has not had an influence on their feelings towards it. *Influence* includes when the person feels how much they have used their prosthesis has had an influence on their feelings towards it.

0. No influence

1. Influence

**Amount of use of prosthesis initially.** *No influence* includes when the person feels how much they have used their prosthesis initially (anything they count as early on in their prosthesis use) has not had an influence on their feelings towards it. *Influence* includes when the person feels how much they have used their prosthesis initially (anything they count as early on in their prosthesis use) has had an influence on their feelings towards it.

0. No influence

1. Influence

**Type of prosthesis.** *No influence* includes when the person feels the type of prosthesis they have has not had an influence on their feelings towards it. *Influence* includes when the person feels the type of prosthesis they have has had an influence on their feelings towards it.

0. No influence

1. Influence

**Control method.** *No influence* includes when the person feels the type of control method of their prosthesis has not had an influence on their feelings towards it. *Influence* includes when the person feels the type of control method of their prosthesis has had an

influence on their feelings towards it. *Not applicable* includes when the prosthesis is cosmetic.

- 0. No influence
- 1. Influence
- 2. Not applicable

**Repeated changes to prosthesis.** *No influence* includes when the person feels the number of changes to their prosthesis has not had an influence on their feelings towards it. *Influence* includes when the person feels the number of changes to their prosthesis has had an influence on their feelings towards it.

- 0. No influence
- 1. Influence

**Customisation of appearance.** *No influence* includes when the person feels their personal customisation (either directly or via another person) of their prosthesis has not had an influence on their feelings towards it. *Influence* includes when the person feels their personal customisation (either directly or via another person) of their prosthesis has had an influence on their feelings towards it. *Not applicable* includes when the person has not personally customised their prosthesis.

- 0. No influence
- 1. Influence
- 2. Not applicable

**Satisfaction with prosthesis.** *No influence* includes when the person feels their satisfaction with their prosthesis has not had an influence on their feelings towards it. *Influence* includes when the person feels their satisfaction with their prosthesis has had an influence on their feelings towards it.

- 0. No influence
- 1. Influence

**Satisfaction with prosthesis functionality.** *No influence* includes when the person feels their satisfaction with their prosthesis functionality has not had an influence on their feelings towards it. *Influence* includes when the person feels their satisfaction with their prosthesis functionality has had an influence on their feelings towards it.

0. No influence

1. Influence

**Satisfaction with prosthesis appearance.** *No influence* includes when the person feels their satisfaction with their prosthesis appearance has not had an influence on their feelings towards it. *Influence* includes when the person feels their satisfaction with their prosthesis appearance has had an influence on their feelings towards it.

0. No influence

1. Influence

**Satisfaction with prosthesis fitting.** *No influence* includes when the person feels their satisfaction with the fit of their prosthesis has not had an influence on their feelings towards it. *Influence* includes when the person feels their satisfaction with the fit of their prosthesis has had an influence on their feelings towards it.

0. No influence

1. Influence

**Satisfaction with prosthesis comfort/weight.** *No influence* includes when the person feels their satisfaction with either the comfort or weight of their prosthesis has not had an influence on their feelings towards it. *Influence* includes when the person feels their satisfaction either the comfort or weight of their prosthesis has had an influence on their feelings towards it.

0. No influence

1. Influence

**Satisfaction with prosthesis robustness.** *No influence* includes when the person feels their satisfaction with the robustness their prosthesis (i.e., how well their prosthesis does not break or fall apart) has not had an influence on their feelings towards it. *Influence* includes when the person feels their satisfaction with the robustness of their prosthesis (i.e., how well their prosthesis does not break or fall apart) has had an influence on their feelings towards it.

0. No influence

1. Influence

**Satisfaction with prosthesis reliability.** *No influence* includes when the person feels their satisfaction with the reliability their prosthesis (i.e., how well their prosthesis responds once the hand or hook is opened or closed) has not had an influence on their feelings towards it. *Influence* includes when the person feels their satisfaction with the reliability their prosthesis (i.e., how well their prosthesis responds once the hand or hook is opened or closed) has had an influence on their feelings towards it. *Not applicable* includes when the prosthesis is cosmetic.

0. No influence
1. Influence
2. Not applicable

**Satisfaction with prosthesis response speed.** *No influence* includes when the person feels their satisfaction with the response speed of their prosthesis (i.e., how quickly their prosthesis responds once the hand or hook is opened or closed) has not had an influence on their feelings towards it. *Influence* includes when the person feels their satisfaction with the response speed of their prosthesis (i.e., how quickly their prosthesis responds once the hand or hook is opened or closed) has had an influence on their feelings towards it. *Not applicable* includes when the prosthesis is cosmetic.

0. No influence
1. Influence
2. Not applicable

**Satisfaction with prosthesis noise.** *No influence* includes when the person feels their satisfaction with the noise of their prosthesis (i.e., the noise the prosthesis makes whilst being used) has not had an influence on their feelings towards it. *Influence* includes when the person feels their satisfaction with the noise of their prosthesis (i.e., the noise the prosthesis makes whilst being used) has had an influence on their feelings towards it. *Not applicable* includes when the prosthesis is cosmetic.

0. No influence
1. Influence
2. Not applicable

**Proficiency with prosthesis.** *No influence* includes when the person feels how skilled they are in using their prosthesis has not had an influence on their feelings towards it.

*Influence* includes when the person feels how skilled they are in using their prosthesis (i.e., feeling proficient in using it) has had an influence on their feelings towards it.

- 0. No influence
- 1. Influence

**Benefits the prosthesis provides.** *No influence* includes when the person feels the benefits (physical or cosmetic functions) the prosthesis provides has not had an influence on their feelings towards their prosthesis. *Influence* includes when the person feels benefits (physical or cosmetic functions) the prosthesis provides has had an influence on their feelings towards their prosthesis.

- 0. No influence
- 1. Influence

**Phantom limb sensations.** *No influence* includes when the person feels their phantom limb sensations have had no influence on their feelings towards their prosthesis. *Influence* includes when the person feels their phantom limb sensations have had an influence on their feelings towards their prosthesis. *Not applicable* includes when the person reports having no phantom sensations during use of their prosthesis.

- 0. No influence
- 1. Influence
- 2. Not applicable

**Phantom limb sensations position.** *No influence* includes when the position of their phantom limb sensations (relative to the prosthesis) have had no influence on their feelings towards their prosthesis. *Influence* includes when the person feels the position of their phantom limb sensations (relative to the prosthesis) have had an influence on their feelings towards their prosthesis. *Not applicable* includes when the person reports having no phantom sensations during use of their prosthesis.

- 0. No influence
- 1. Influence
- 2. Not applicable

**Sensory feedback from prosthesis.** *No influence* includes when the person feels their sensory feedback (e.g., feedback on stump or other body part, specific sounds) from their

prosthesis has not had an influence on their feelings towards it. *Influence* includes when the person feels their sensory feedback (e.g., feedback on stump or other body part, specific sounds) from their prosthesis has had an influence on their feelings towards it.

0. No influence

1. Influence

**Awareness of prosthesis.** *No influence* includes when the person feels their awareness of their prosthesis has not had an influence on their feelings towards it. *Influence* includes when the person feels their awareness of their prosthesis has had an influence on their feelings towards it.

0. No influence

1. Influence

**Need for planning tasks in advance.** *No influence* includes when the person feels their need for planning tasks in advance (e.g., they can't perform at least some tasks without planning ahead) before using their prosthesis has not had an influence on their feelings towards their prosthesis. *Influence* includes when the person feels their need for planning tasks in advance (e.g., they can't perform at least some tasks without planning ahead) before using their prosthesis has had an influence on their feelings towards their prosthesis.

0. No influence

1. Influence

**Body image.** *No influence* includes when the person feels their body image (e.g. how positive or negative they feel about their body) before using their prosthesis has not had an influence on their feelings towards their prosthesis. *Influence* includes when the person feels their body image (e.g. how positive or negative they feel about their body) before using their prosthesis has had an influence on their feelings towards their prosthesis.

0. No influence

1. Influence

**Positive mindset.** *No influence* includes when the person feels how positive or determined they were towards being successful in using their prosthesis has not had an influence on their feelings towards their prosthesis. *Influence* includes when the person feels



how positive or determined they were towards being successful in using their prosthesis has had an influence on their feelings towards their prosthesis.

- 0. No influence
- 1. Influence

**Amount of negative attention.** *No influence* includes when the person feels the amount of negative attention that they perceive to receive from others towards their prosthesis, or themselves having limb-loss, has not had an influence on their feelings towards their prosthesis. *Influence* includes when the person feels the amount of negative attention that they perceive to receive from others towards their prosthesis, or themselves having limb-loss, has had an influence on their feelings towards their prosthesis.

- 0. No influence
- 1. Influence

### **Factors influencing temporary feelings towards prosthesis**

**Note:** Temporary feelings are where feelings towards a person's prosthesis change temporarily (compared to overall) as a result of something specific, i.e., the prosthesis feels more or less part of the user than it usually does. **For the beginning of the code use 'Factors influencing temporary – ', followed by the relevant code below (factor name in bold).**

**Prosthesis being removed.** *No influence* includes when the person feels their prosthesis being removed has not temporarily influenced feelings towards their prosthesis. *Influence* includes when the person feels their prosthesis being removed has temporarily influenced feelings towards their prosthesis.

- 0. No influence
- 1. Influence

**Prosthesis being broken.** *No influence* includes when the person feels their prosthesis being broken has not temporarily influenced feelings towards their prosthesis. *Influence* includes when the person feels their prosthesis being broken has temporarily influenced feelings towards their prosthesis.

- 0. No influence
- 1. Influence

**Prosthesis causes damage/discomfort.** *No influence* includes when the person feels their prosthesis causing damage or discomfort to their body (e.g., stump or other body part) whilst wearing it has not temporarily influenced feelings towards their prosthesis. *Influence* includes when the person their prosthesis causing damage or discomfort to their body (e.g., stump or other body part) whilst wearing it has temporarily influenced feelings towards their prosthesis.

0. No influence

1. Influence

**Prosthesis falls/loose fitting.** *No influence* includes when the person feels their prosthesis either falling off or having a loose fitting in the socket has temporarily influenced feelings towards their prosthesis. *Influence* includes when the person their prosthesis either falling off or having a loose fitting in the socket has temporarily influenced feelings towards their prosthesis.

0. No influence

1. Influence

**Others noticing prosthesis and reacting negatively.** *No influence* includes when the person feels that others noticing and reacting negatively towards their prosthesis, or themselves having limb-loss, has not temporarily influenced feelings towards their prosthesis. *Influence* includes when the person feels that others noticing their prosthesis has temporarily influenced feelings towards their prosthesis.

0. No influence

1. Influence

**Capability of prosthesis for a specific activity.** *No influence* includes when the person feels how useful their prosthesis is for a specific activity has not temporarily influenced feelings towards their prosthesis. *Influence* includes when the person feels how useful their prosthesis is for a specific activity has temporarily influenced feelings towards their prosthesis.

0. No influence

1. Influence

**Issue with control of prosthesis.** *No influence* includes when the person feels their issue with control of their prosthesis (e.g., poor placement of electrodes in a myoelectric prosthesis causing the prosthesis to not respond accordingly) has not temporarily influenced feelings towards their prosthesis. *Influence* includes when the person feels their issue with control of their prosthesis (e.g., poor placement of electrodes in a myoelectric prosthesis causing the prosthesis to not respond accordingly) has not temporarily influenced feelings towards their prosthesis. *Not applicable* includes when the prosthesis is cosmetic.

0. No influence
1. Influence
2. Not applicable

### **Overall outcomes of feelings towards prosthesis**

**Note:** Overall outcomes are something specific happening as a result of the person's feelings towards their prosthesis, where the outcome is general in nature (compared to a temporary outcome). **For the beginning of the code use 'Overall outcomes – ', followed by the relevant code below (factor name in bold).**

**Amount of use of prosthesis.** *No outcome* includes when the person thinks their feelings towards their prosthesis has not influenced how much they use their prosthesis. *Outcome* includes when the person's feelings towards their prosthesis has influenced how much they use their prosthesis.

0. No outcome
1. Outcome

**Proficiency with prosthesis.** *No outcome* includes when the person's feelings towards their prosthesis has not influenced how well they can use their prosthesis (generally or for specific activities). *Outcome* includes when the person's feelings towards their prosthesis has influenced how well they can use their prosthesis (generally or for specific activities).

0. No outcome
1. Outcome

**Awareness of prosthesis.** *No outcome* includes when the person's feelings towards their prosthesis has not influenced their awareness of their prosthesis. *Outcome* includes when the person's feelings towards their prosthesis has influenced their awareness of their prosthesis.

- 0. No outcome
- 1. Outcome

**Need to plan tasks in advance.** *No outcome* includes when the person's feelings towards their prosthesis has not influenced their need to plan tasks in advance. *Outcome* includes when the person's feelings towards their prosthesis has influenced their need to plan tasks in advance.

- 0. No outcome
- 1. Outcome

**Body image overall.** *No outcome* includes when the person's feelings towards their prosthesis has not influenced their body image (e.g. how positive or negative they feel about their body) overall. *Outcome* includes when the person's feelings towards their prosthesis has influenced their body image (e.g. how positive or negative they feel about their body) overall.

- 0. No outcome
- 1. Outcome

**Satisfaction with prosthesis.** *No outcome* includes when the person's feelings towards their prosthesis has not influenced their satisfaction with their prosthesis overall. *Outcome* includes when the person's feelings towards their prosthesis has influenced their satisfaction with their prosthesis overall.

- 0. No outcome
- 1. Outcome

**Expectation of prosthesis to behave as real arm.** *No outcome* includes when the person's feelings towards their prosthesis has not influenced their expectation of their prosthesis to behave as a real arm (e.g., respond in a natural way). *Outcome* includes when the person's feelings towards their prosthesis has influenced their expectation of their prosthesis to behave as a real arm (e.g., respond in a natural way).

- 0. No outcome

1. Outcome

**Body's reaction with hand dominance.** *No outcome* includes when the person's feelings towards their prosthesis has not influenced their body's reaction in terms of hand dominance (e.g., for the dominant side to respond in a natural way). *Outcome* includes when the person's feelings towards their prosthesis has influenced their body's reaction in terms of hand dominance (e.g., for the dominant side to respond in a natural way).

0. No outcome

1. Outcome

**Expectation of others to care for prosthesis.** *No outcome* includes when the person's feelings towards their prosthesis has not influenced their expectation of whether others will care for their prosthesis. *Outcome* includes when the person's feelings towards their prosthesis has influenced their expectation of whether others will care for their prosthesis.

0. No outcome

1. Outcome

**Restriction in using one type of prosthesis or specific device.** *No outcome* includes when the person's feelings towards their prosthesis has not influenced their restriction in using one type of prosthesis or specific prosthesis. *Outcome* includes when the person's feelings towards their prosthesis has influenced their restriction in using one type of prosthesis or specific prosthesis.

0. No outcome

1. Outcome

**Temporary outcomes of feelings towards prosthesis**

**Note:** Temporary outcomes are something specific happening as a result of the person's feelings towards their prosthesis, where the outcome is temporary in nature (compared to overall). **For the beginning of the code use 'Temporary outcomes – ', followed by the relevant code below (factor name in bold).**

**Body image changing temporarily.** *No outcome* includes when the person's feelings towards their prosthesis has not influenced their body image (e.g. how positive or negative they feel about their body) changing temporarily. *Outcome* includes when the person's feelings towards their prosthesis has influenced their body image (e.g. how positive or negative they feel about their body) changing temporarily.

0. No outcome

1. Outcome

**Negative feeling from others touching prosthesis.** *No outcome* includes when the person's feelings towards their prosthesis has not influenced them having an emotional response from someone touching their prosthesis. *Outcome* includes when the person's feelings towards their prosthesis has influenced them having a negative feeling if someone touches their prosthesis.

0. No outcome

1. Outcome

**Negative feeling from others noticing prosthesis.** *No outcome* includes when the person's feelings towards their prosthesis has not influenced them having a negative feeling from someone noticing their prosthesis (in terms of wearing it or not wearing it). *Outcome* includes when the person's feelings towards their prosthesis has influenced them having a negative feeling if someone notices their prosthesis (in terms of wearing it or not wearing it).

0. No outcome

1. Outcome

**Negative feeling when prosthesis broken.** *No outcome* includes when the person's feelings towards their prosthesis has not influenced them having a negative feeling when their prosthesis was broken or not functioning. *Outcome* includes when the person's feelings towards their prosthesis has influenced them having a negative feeling when their prosthesis was broken or not functioning.

0. No outcome

1. Outcome

**Negative feeling towards prosthesis projected towards self.** *No outcome* includes when the person's feelings towards their prosthesis has not influenced them having a negative

feeling when their prosthesis was broken or not functioning. *Outcome* includes when the person's feelings towards their prosthesis has influenced them having a negative feeling when their prosthesis was broken or not functioning.

0. No outcome

1. Outcome

**Feeling incomplete without prosthesis.** *No outcome* includes when the person's feelings towards their prosthesis has not influenced them feeling incomplete without their prosthesis. *Outcome* includes when the person's feelings towards their prosthesis has influenced them feeling incomplete without their prosthesis.

0. No outcome

1. Outcome

**Lack of emotional replacement from hand to prosthesis.** *No outcome* includes when the person's feelings towards their prosthesis has not influenced how their emotions from replacing their amputated hand with a prosthesis. *Outcome* includes when the person's feelings towards their prosthesis has influenced how their emotions from replacing their amputated hand with a prosthesis. *Not applicable* includes when the person has congenital limb absence.

0. No outcome

1. Outcome

2. Not applicable

## Appendix F: Coding spreadsheet data for qualitative study

Table F1

*Data from coding spreadsheet for qualitative study*

Participant number	2	3	6	1	5	8	7	4	10	11
Feelings towards prosthesis										
Overall feeling towards prosthesis	3	1	1	1	2	2	2	2	2	3
Emotional connection	1	1	1	10	0	0	0	0	10	10
Feels natural/not foreign	10	1	10	1	10	0	0	0	0	1
Integrated into body image	1	1	1	1	0	0	0	0	0	10
Integrated into self	10	1	1	1	10	0	10	0	10	10
Wearing glasses/shoes/ backpack analogy	1	10	1	10	1	1	1	1	1	10
Expendable	10	10	0	0	1	10	1	1	10	10
Feelings towards Prosthesis change										
gradually over time	0	0	1	0	0	0	10	0	0	1
Feelings towards prosthesis change temporarily	1	1	1	1	1	0	10	1	1	1
Desire or need for their prosthesis to feel part of them										
	1	1	9	10	0	1	0	9	1	1
Factors influencing feelings towards prosthesis										
Being born without arm(s)	1	1	1	2	10	10	10	10	10	2
Being born with arm(s)	2	2	2	10	2	10	10	10	10	10
Length of time with prosthesis										
	0	1	1	1	0	10	10	0	0	1
Age of first use of prosthesis	1	1	1	10	10	10	1	10	10	10
Amount of use of prosthesis										
	1	1	1	1	0	0	10	1	0	1
Amount of use initially	10	10	1	10	10	10	10	1	10	10
Type of prosthesis										
	1	1	1	1	0	1	1	1	1	1
Control method	10	10	10	2	2	10	10	1	1	1
Repeated changes to prosthesis										
	10	10	10	10	10	10	10	1	10	10
Customisation of appearance	10	10	10	10	10	10	10	10	10	1
Satisfaction with prosthesis										
	10	10	10	10	0	10	10	10	10	10
Satisfaction with functionality										
	1	10	1	1	10	1	1	1	1	1
Satisfaction with appearance	1	10	10	1	10	0	1	1	0	1
Satisfaction with fitting	1	10	10	10	10	1	10	1	10	1
Satisfaction with comfort/weight										
	1	10	1	1	0	1	10	1	10	1
Satisfaction with robustness	10	10	10	10	10	10	10	1	10	10



Satisfaction with reliability	10	10	1	10	10	10	1	1	10	1
Satisfaction with response speed	10	1	10	10	10	10	10	1	10	1
Satisfaction with noise	10	10	10	2	2	10	10	1	10	10
Proficiency with prosthesis	10	1	1	10	10	10	10	10	10	1
Benefits the prosthesis provides	1	10	1	1	10	1	1	10	10	1
Phantom limb sensations	2	2	2	0	2	1	10	1	0	1
Phantom limb position	2	2	2	10	2	0	10	0	0	0
Sensory feedback from prosthesis	10	1	10	0	10	2	1	10	1	1
Awareness of prosthesis	1	1	1	1	0	1	10	1	1	1
Need for planning tasks in advance	10	10	10	10	10	1	10	1	1	1
Body image	9	9	9	0	1	0	9	10	0	10
Positive mindset	10	10	10	10	10	10	10	10	10	1
Amount of negative attention	10	10	1	10	10	10	10	1	10	10
Factors influencing temporary feelings towards prosthesis										
Removing the prosthesis	10	1	10	10	10	10	10	1	1	0
Prosthesis being broken	10	10	1	1	0	10	10	10	10	10
Prosthesis causes damage/discomfort	10	10	10	10	10	10	10	1	10	1
Prosthesis falls/loose fitting	10	10	10	10	10	10	10	1	10	1
Others noticing prosthesis and reacting negatively	1	10	1	1	1	10	10	10	10	1
Capability of prosthesis for a specific activity	10	10	1	1	0	10	10	10	1	1
Issue with control of prosthesis	10	10	10	2	2	2	10	10	1	1
Overall outcomes of feelings towards prosthesis										
Amount of use of prosthesis	1	9	0	1	0	1	10	1	1	1
Proficiency with prosthesis	1	1	1	1	1	1	10	10	1	1
Awareness of prosthesis	0	1	1	1	0	1	10	0	1	1
Need for planning tasks in advance	1	1	1	1	1	1	10	1	10	10
Body image changed overall	0	0	1	0	0	0	10	0	0	1
Satisfaction with prosthesis	10	1	1	1	0	0	10	10	1	1
Expectation of prosthesis to behave as real arm	10	10	10	10	10	10	10	1	10	10
Body's reaction with hand dominance	10	10	1	10	0	10	10	10	10	10
Expectation of others to care for prosthesis	10	10	10	10	10	10	10	1	10	10
Restriction in using one prosthetic type/device	10	10	0	10	10	10	10	1	10	10

Temporary outcomes of feelings  
towards prosthesis

Body image										
changing temporarily	10	1	0	10	0	10	10	10	10	10
Negative feeling from others touching prosthesis	10	1	10	10	10	10	10	10	10	10
Negative feeling from others noticing prosthesis	10	10	1	10	10	10	10	1	10	10
Negative feeling when prosthesis broken	10	10	1	1	0	10	10	1	10	10
Negative feelings towards prosthesis projected towards self/body	10	1	1	10	10	10	10	1	10	10
Feeling incomplete without prosthesis	10	10	1	10	1	10	10	0	10	0
Lack of emotional replacement from hand to prosthesis	10	10	10	10	10	10	10	1	10	10

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*Note:* Red text = Factors that emerged through interviews

## Appendix G: Ethics application approval for qualitative study



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27 April 2016

Dear Andrew,

**RE: ETHICS APPLICATION HSCR 16-32 – A Content Analysis of factors associated with embodiment of upper limb prostheses**

Based on the information you provided, I am pleased to inform you that application HSCR16-32 has been approved.

If there are any changes to the project and/ or its methodology, please inform the Panel as soon as possible by contacting [Health-ResearchEthics@salford.ac.uk](mailto:Health-ResearchEthics@salford.ac.uk)

Yours sincerely,

A handwritten signature in black ink, appearing to read 'Sue McAndrew', written over a light grey rectangular background.

Sue McAndrew  
Chair of the Research Ethics Panel

## **Appendix H: PIS, Consent form and Debrief sheet**

### **H.1 Participant information sheet**

#### **Participant Information Sheet – Version 1 06/04/16**

**Title of study:** A Content Analysis of factors associated with embodiment of upper limb prostheses

**Name of Researcher:** Andrew Hodrien

Thank you for taking the time to find out more about this research study. To consider if you wish to participate in the research please read the below information detailing why you have been invited, what will be involved, and how the study is being managed. If you wish to find out any further details please contact me on the email address at the bottom.

#### **What is the purpose of this study?**

Some prosthesis users report that they experience their prosthetic limb as a part of their body, whilst others do not. The aim of this study is to identify a range of factors which are associated with upper limb prosthesis embodiment (i.e., the feeling that a prosthetic limb is a ‘part of’ the user). Limited previous research has explored prosthesis embodiment and the factors that might influence whether or not a prosthetic limb feels like a part of the body. A further aim of this study is to provide information which will guide a future investigation of the use of computer techniques, such as virtual reality, to influence feelings of embodiment.

#### **Why have I been invited to take part?**

We are inviting anyone over the age of 18, who has had the experience of using an upper limb prosthesis.

#### **Do I have to take part?**

No, this is a completely voluntary study and it is up to you to decide if you wish to participate once you have read all the information. Take at least 24 hours to consider your involvement. If you do wish to participate you will complete a consent form but anytime during the study you will be able to withdraw (with no given reason) if you later decide you no longer wish to be involved.

It is entirely up to you whether to take part. Taking the time to read all of the information provided about the study will help you come to an informed decision. If you decide to participate, you will be asked to complete and sign a consent form – a copy of which I have attached **here** so you can see what is involved (**you are unable to fill this in but I will email you the form to complete**). Remember, however that if at any time during the study you decide you no longer wish to participate, you can withdraw or end your participation without needing to give a reason.

### **What will happen to me if I take part?**

Once you email me to confirm your interest in participating, I will email you an electronic consent form to complete and email back to me. Once the interview begins, questions will be emailed to you one by one. It is up to you how much information you would like to include in your responses, and you will be free to decline to answer any of the questions if you wish. I will discuss with you a schedule of time in which to complete the interview over email, but this is flexible depending on your requirements. Once all the questions have been covered and you are happy to finish the interview, I will send you a sheet with final information about the study and a reminder about how to withdraw your data if you wish to.

### **Expenses and payments?**

The research will be entirely voluntary so you will not be paid for your participation in the study.

### **What are the possible disadvantages and risks of taking part?**

We understand that circumstances around the use of prostheses or issues involved in actual use of a prosthetic limb could be of a sensitive nature so discussing these may be difficult for you. However, the study is designed to minimise this and if any particular question is uncomfortable

to discuss you do not need to answer it. If you wish to withdraw from the study, you can do so at any time without giving reason. If you wish to withdraw your data after the study is complete, you can email the researcher and request your data is removed which can be done up to 18/09/2016.

### **What are the possible benefits of taking part?**

We cannot guarantee that you will benefit from taking part in this study, but it is hoped that the knowledge generated will ultimately help to improve how professionals such as prosthetists and medical doctors approach upper limb amputee rehabilitation.

### **What if there is a problem?**

If there is any problem you can raise this with the researcher Andrew Hodrien (contact details at the bottom) or if this is not suitable then contact his main supervisor –

Dr. Adam Galpin. Email: [A.J.Galpin@salford.ac.uk](mailto:A.J.Galpin@salford.ac.uk). Telephone: 0161 295 7146. Senior Lecturer, School of Health Sciences, L812b Allerton Building, University of Salford, Salford, Manchester, M6 6PU.

Or -

Anish Kurien, Research Centres Manager, Email: [a.kurien@salford.ac.uk](mailto:a.kurien@salford.ac.uk). Telephone: 0161 295 5276. G.08 Joule House Acton Square, University of Salford, M5 4WT.

If you wish to seek support or further information relevant to your circumstances or experiences then I will provide here the contact details of amputee/prosthesis associations:

**The limbless association:** [www.limbless-association.org/](http://www.limbless-association.org/) - for general advice.

**Limbpower:** [www.limbpower.com](http://www.limbpower.com) – for general advice or activities.

**The British Limbless ex-servicemen's association:** <https://blesma.org/> - if you have served in the British military.

Additionally, if through discussing sensitive experiences you feel upset about this you could enquire about counselling services by contacting your GP or your limb centre (if applicable), or contacting the NHS helpline on free telephone number 111 for further advice.

**Will my taking part in the study be kept confidential?**

Your identity will be kept confidential by conducting interviews through a University password-protected email account and any data transferred to documents will be anonymised. Also, you will receive a unique research code which you can provide to me if you wish to remove yourself from the study and then your data linked to this code will be deleted. If one of my supervisors needs to check my analysis of your data, they may have access to it but it will be from the anonymised files not my original emails with you (which could naturally contain your name).

**What will happen if I don't carry on with the study?**

If you decide not to carry on with the study you can provide your research code and then your data will be deleted without the need to provide a reason for this. This can be done up until 18/09/2016.

**What will happen to the results of the research study?**

The results will be disseminated through my PhD thesis which this study forms part of, along with publications and/or presentations in academic journal articles and conferences. These outputs will contain a pseudonym so that your identity will remain confidential.

**Who is organising or sponsoring the research?**

The research is being organised by the Centre for Health Sciences Research, University of Salford, Salford M6 6PU. The research is being conducted as part of a PhD project funded by the University of Salford.

**Further information and contact details:**

If you would like to participate in the study or enquire about any additional information please contact Andrew Hodrien at [a.d.hodrien@edu.salford.ac.uk](mailto:a.d.hodrien@edu.salford.ac.uk)

Supervised by Dr. Adam Galpin. Email: [A.J.Galpin@salford.ac.uk](mailto:A.J.Galpin@salford.ac.uk). Telephone: 0161 295 7146. Senior Lecturer, School of Health Sciences, L812b Allerton Building, University of Salford, Salford, Manchester, M6 6PU.

Thank you for taking the time to read about this study and for considering participation.



## H.2 Consent form

### CONSENT FORM

**Title of study:** A Content Analysis of factors associated with embodiment of upper limb prostheses

**Name of Researcher:** Andrew Hodrien

Please complete and sign this form **after** you have read and understood the study information sheet. Read the statements below and delete yes or no, as applicable in the box on the right-hand side.

- |    |   |        |
|----|---|--------|
| 1. | I confirm that I have read and understand the study information sheet version 1, dated 06/04/2016, for the above study. I have had opportunity to consider the information and ask questions which have been answered satisfactorily. | Yes/No |
| 2. | I understand that my participation is voluntary and that I am free to withdraw at any time, without giving any reason, and without my rights being affected.  | Yes/No |
| 3. | I understand that I can withdraw until 18/09/2016 and that any information given until then will be included in the analysis (but not published anywhere) and all data will be removed if I decide to withdraw.                       | Yes/No |
| 4. | I agree to participate by being interviewed.  | Yes/No |
| 5. | I understand that my personal details will be kept confidential and not revealed to people outside the research team.   | Yes/No |
| 6. | I understand that my anonymised data will be used in the researcher's Thesis, other academic publications, and conferences presentations.   | Yes/No |

7. I agree to take part in the study.

Yes/No
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\_\_\_\_\_  
\_\_\_\_\_

**Name of participant  
initials or  
signature)**

\_\_\_\_\_

**Date**

**Signature (type  
add electronic**

\_\_\_\_\_  
\_\_\_\_\_

**Name of person taking consent**

\_\_\_\_\_

**Date**

**Signature**

### H.3 Debrief sheet

## Debrief Sheet

**Title of study:** A Content Analysis of factors associated with embodiment of upper limb prostheses

**Name of Researcher:** Andrew Hodrien

Thank you for taking the time to participate in our research and share your experiences. These will be used to help guide development of a later experiment which aims to encourage prosthesis embodiment. The information you have provided will also help further general understanding of prosthesis embodiment and prosthesis use which could impact upon how rehabilitation is conducted.

If you wish to seek support or further information relevant to your circumstances or experiences then I will provide here the contact details of amputee/prosthesis associations:

**The limbless association:** [www.limbless-association.org/](http://www.limbless-association.org/) - for general advice.

**Limbpower:** [www.limbpower.com](http://www.limbpower.com) – for general advice or activities.

**The British Limbless ex-servicemen's association:** <https://blesma.org/> - if you have served in the British military.

We hope your experience of the email interview has been comfortable for you, however if through discussing sensitive experiences you feel upset about this you could enquire about counselling services by contacting your GP or your limb centre (if applicable), or contacting the NHS helpline on free telephone number 111 for further advice.

If you wish to withdraw your data from the study can you please contact the researcher and provide him with your unique participant research code which he gave you and then he will remove your data. This can be done up until 18/09/2016.

Your emails and contact details will be deleted once the research phase has been completed (18/09/2016). However, if you wish to be contacted by the Centre for Health Sciences Research at the University of Salford about future studies relevant to you, please read the following information: <http://www.salford.ac.uk/research/health-sciences/research-groups/research-participant-register>.

Many thanks again for your time participating in our research.

For any further information or to request withdrawal from the study contact –

Andrew Hodrien: [a.d.hodrien@edu.salford.ac.uk](mailto:a.d.hodrien@edu.salford.ac.uk)

Supervised by Dr. Adam Galpin. Email: [A.J.Galpin@salford.ac.uk](mailto:A.J.Galpin@salford.ac.uk). Telephone: 0161 295 7146. Senior Lecturer, School of Health Sciences, L812b Allerton Building, University of Salford, Salford, Manchester, M6 6PU.

## Appendix I: Interview transcript example from qualitative study

Participant number - 11

I: OK to start with a broad question, please can you describe your relationship with your prosthesis (e.g., How do you view or feel about your prosthesis)? Please provide as much detail as you are happy/able to share.

P: My prosthesis has become part of my daily routine. I consider it a tool, however, I refer to it as "my arm". It is cumbersome, bulky, heavy, and uncomfortable to wear. The harness hurts my upper back after a few hours of wearing it, and makes my back and neck sweat. I have a love / hate relationship with "my arm". I hate the way it feels when I put it on, and how uncomfortable it is. I feel uncomfortable wearing it in public, because people stare and often treat me different. There are days that I just don't want to deal with it at all, and take a day off from wearing it. At the same time, I love that I am able to have a prosthetic arm. I love that it helps my life easier, and gives me more independence, than without it. I just wish it was lighter, less bulky, and NO harness.

I really hate the harness! It limits my clothing choices. As a women, it is hard to feel "pretty" with a strap wrapped around my left armpit and across my back. When I drive with my arm on it can feel overwhelming. With the harness tugging across my back, and the seat belt strapped across my front, I feel like I can't move. I have at times, pulled over, and taken my arm off because it feels so uncomfortable.

I like my arm, it's a tool that makes my life easier, but it's never going to replace the arm I lost

I: Thanks very much for detailing your thoughts and feelings towards your prosthesis. That is interesting that you refer to it as your arm but that you consider it a tool. I would like to ask further about that to clarify how you feel.

Aside from what you have mentioned already, in what ways do you feel differently about your prosthesis, compared to your other, intact arm?

P: I call it my arm because it has become a part of me, but it is in reality a tool that has been customized to resemble my missing arm. It is my arm because it is now the arm I use to accomplish tasks that are difficult, or nearly impossible to do with just one arm. I depend on my arm to help me complete tasks independently. It took a while for me to accept wearing a prosthetic arm. At first, after the accident, the word "prosthetic" was foreign, and I didn't want to hear it. I decided that I could try wearing it after my son-in-law told me to think of it as a tool, not an arm replacement. It was easier to accept wearing a prosthetic arm by telling myself that it was a tool. After a few months of getting used to wearing it, I started calling it "my arm". It has not replaced my missing arm, but it has become a big part of my life.

My prosthetic arm can be annoying at times compared to my intact arm. It is bulky, and hard, heavy, and it hurts people if they bump into me. It often gets in the way, and it cannot accomplish certain tasks that I need my intact arm for. My prosthesis is definitely a good substitute helper, but my intact arm is much more superior.

I: Thanks for that. Some things you mentioned I may come back to later. However, just to elaborate further on your overall feelings, as you said you consider your prosthesis as a tool, and call it your arm because of it providing you functionality, does that mean it is 'part of you' in the sense of you using it often, or feeling part of your body/integrated into your 'self'? Of course, if you think it is neither, or both of these, please let me know.

That is interesting what you mentioned about it being easier for you to initially think of it as a tool. Depending on how you answer above, does this mean your actual feelings towards your prosthesis changed over a period of time or just how you referred to it (i.e., calling it your arm later on)?

Please let me know if you are unsure with anything I asked above.

P: My feelings did change over time regarding my prosthesis. At first it was hard to accept that I needed it or wanted a prosthesis at all. As I slowly integrated my prosthesis into my daily routine, I started thinking of it differently. I started to "like" using it more and more. I realized how it was helping me be more independent. I think that it has become a part of me in the sense of providing functionality and using it often, and because it has been integrated into my life. At first I really had to think about how to use it, and what to use it for. After a couple months, I found myself using it for different tasks without even having to think about it. It had become to feel "natural", more like how I use my intact arm. At first it felt foreign, and now it is my "normal".

I: Thanks for further detailing your feelings. Just to follow up on a few things you mentioned. From my understanding, your prosthesis feels natural to you rather than a foreign object, and that one reason you feel it is part of you is because of the functionality it provides. Would that be correct?

Also, from what you said about integrating it into your life and using it for more tasks, do you feel how much you have used it has influenced your feelings of it being part of you?

P: Yes, over time, and the more I used my prosthesis, it has become to feel more natural to me. I think that it has become part of me because of the functionality it provides for me, and integrating it into my life has definitely influenced the way I feel about it. I have talked to other upper extremity amputees, and many didn't really give their prosthesis a chance because of how uncomfortable the harness is. I know of 3 amputees that took their prosthesis home, but never used them consistently. They all said that they tried wearing their prosthesis, but got frustrated, threw them in a closet, and never used it again. I really had some frustration with my prosthesis at first, but I was determined to give it a try. I took it slow at first, and gradually increased how long I would wear it each day. At first it took a lot of concentration, and thinking to make it function. It became like a challenge to figure out what I could use it for. The more I used it, the better I felt about my prosthesis. After a few months I was using without even thinking about it.

I: Thanks for further detailing your feelings. Just picking up on the last point you made about using your prosthesis without thinking about it, do you think your conscious awareness of your prosthesis (how much you are generally aware of, or need to think about it during a task) has influenced your prosthesis feeling part of you?

P: Yes, the more natural it has become to do a task with my prosthesis has definitely influenced the feeling of my prosthesis being part of me. The ability to use my prosthesis without having to think about it, took some time and training for my brain and residual arm (muscles, shoulders), to connect or synchronize. As using my prosthetic became more of a normal or routine part of the day for me, the better I felt about it. Not having to consciously think about each movement has made it easier, and contributed to the feeling of "my arm" being part of me.

I: Thanks, that is interesting to hear your thoughts about reduced awareness having an influence on your prosthesis feeling part of you.

Can you think of any other reasons which may have influenced your feelings?

P: I believe having a positive mindset that I was going to be successful, and consistency with wearing and using "my arm" each day had some impact on how I feel as well. At first, it took a lot of courage to go out in public with my arm. I learned quickly to avoid looking at people (because of all the stares), and to concentrate on the task at hand (like at the grocery store when I use my arm to help bag produce). I decided early on that I was going to not worry about what people thought when they look at me with or without my arm. I decided early on that I was going have a positive attitude, and not let anything stop me from living a full life as an amputee. So I guess having a positive mindset and courage, have also influenced my feelings about "my arm".

I: Thanks, that is a really fascinating point about how having a positive mindset has influenced your feelings towards your prosthesis.

Earlier you mentioned that your feelings have changed over time. I wanted to check, aside from the greater use of your prosthesis, does this mean you think the length of



time you have had it for has influenced it feeling part of you?

Of course, I appreciate it may be difficult to disentangle the influence of time and use of your prosthesis but wanted to see what you think.

P: I do think that the length of time has influenced my feelings about my arm. The first month I had my prosthetic was rough, and frustrating. I had trouble controlling my hook, and moving the elbow, and I developed large fluid filled blisters on my residual arm. However, I kept my mind focused on being successful, and not giving up. I have grown to depend on it to enable me to accomplish tasks that would be near to impossible, or impossible without it. It took time to come to terms with the fact that I need a prosthetic. Over time I have come to accept my life as an amputee, and become more comfortable with my arm. I think it takes time and a lot of patience, and work, to make a prosthetic fit into your life. You definitely need to have an open mind and be prepared for a long term commitment when it comes to prosthetic.

I: Thanks very much. Relating to getting used to your prosthesis, do you think the type of prosthesis you have has had any influence your feelings towards it?

P: I do think that the type of prosthesis has influenced my feelings. When I was in the process of looking for a prosthetist, I wanted the most up to date, and technically advanced prosthesis. The first prosthetist I interviewed did not believe in myoelectric prosthetics, and I was very disappointed. Luckily I found a prosthetist that quickly showed me my options with myoelectric technology. Also, I was able to customize "my arm", and make it very uniquely me. My arm has been customized with the word "love" on the forearm, and I bedazzled it with a few heart shaped rhinestones. I currently have a hook, but I am working towards getting a hand. My myoelectric arm has also sparked a lot of curiosity, interest, and questions from people, especially children. People are amazed when they see me operating my arm. I feel more at ease when people react with interest, and the positive reactions have influenced my feelings. I believe that advanced technology is the only way to go with prosthetics. Having a full manual arm, might work in some situations, but having a "bionic" arm really opens the door to more possibilities.

I: I am happy to hear you have been enjoying the interview so far! The feeling is mutual and I really appreciate what you have been sharing.

Thanks for detailing your thoughts regarding the type of prosthesis. Following from this and specific comments, do you think how satisfied you are with your prosthesis (e.g., with its look or functionality) may have influenced your feelings towards it? As you mentioned customising your prosthesis please also consider this in terms of any impact of appearance on feeling your prosthesis as part of you. Also, as you briefly mentioned a myoelectric compared to a manual prosthesis, please consider any impact of your satisfaction with functionality.

You also touched on another potential aspect so want to ask further about this - you mentioned positive reactions from others has influenced your feelings. Does this mean you feel such reactions have encouraged your prosthesis to feel part of you?

P: For the most part, yes I am satisfied with my prosthesis. The way it has been personally customized has definitely influenced my feelings. When I began the process to shop for a prosthetist, I was very concerned about how a prosthetic arm would look. I had no idea that I could customize a prosthetic. The day I met my prosthetist (Ryan), I was introduced to another upper extremity amputee women (Carrie my mentor / peer visitor), and her prosthetic arm is totally "blinged out" with rhinestones. I was excited for the first time about having a prosthetic arm when I saw her, and her sparkly arm. She was pretty, dressed nice, and her customized prosthetic arm was beautiful! It is very important to me, to be able to express my personality, and femininity. I was very concerned about losing part of myself in this whole transition to life as an amputee. I had envisioned a very boring plain metal prosthetic at first, and was not too thrilled about it. The appearance of my prosthetic has clearly influenced my feelings. The customizing of my arm reflects my personality, and this makes it feel a part of me.

As far as the functionality of my myoelectric arm (it's actually a hybrid myoelectric prosthetic), the advanced technology has definitely influenced the feeling of being a part of me. Just the fact of being able to think about opening my hand (hook) to grab something, makes it feel natural, not mechanical, has influenced my feelings. I think

having a manual prosthetic would be much lighter in weight, but I am not sure it would feel like a natural movement when doing a task. I know that my manual elbow can frustrate me at times, just trying to get it in the correct position at times. I had TMR surgery a year ago, and I am currently in the process of working on getting a full myoelectric prosthetic with a hand instead of a hook. I love the advanced technology, and I feel that I am fortunate to have access to it. The weight of my arm and the harness are what I don't like, and don't feel natural.

The way people react when they see me wearing my arm, has had a huge impact on how I feel. I have had some experiences of bad reactions, that included rude comments, people trying to take pictures with their phones, or acting fearful of me (like I am carrying a gun), and un-apologetically staring... These type of reactions have made me not want to leave my house at times. Then there are the positive reactions, especially from children, that make me feel at ease in public, and normal. The positive reactions contribute to how I feel about being out in public wearing my arm, and normalize being an amputee. Positive reactions from people make me feel proud of my arm, and accomplished with the way I can function better when wearing it. The more normal and at ease I feel in public, makes it feel like my arm is a natural part of me.

- I: Thanks very much for detailing your feelings. That is interesting to hear about the impact of appearance and in particular, customising this, on your feelings towards your prosthesis. Also, thanks for your thoughts on the influence of your satisfaction with functionality. It is fascinating to hear from someone who has undergone TMR in terms of the impact of thinking of opening your hand and the natural movement on feelings towards your prosthesis. As you mentioned you are not satisfied with the weight and harness, do you think these also have an impact on your feelings towards your prosthesis being part of you (I e. It would feel even more part of you if the prosthesis was lighter or had no harness)?

Also, thanks for detailing how others reactions towards you can have an influence on your feelings towards your prosthesis which was interesting to hear about. So, would you say that you have a temporary change in your feelings towards your prosthesis,

based on how someone is responding to you (e.g., feeling like your prosthesis feels even more part of you when you have a positive response)?

P: The weight of my arm and the harness, do impact my feelings. Initially, when I put my arm on during the day, the weight and the pressure of the strap on my back can feel a little overwhelming. As I move through my day using my arm to get tasks done, I am so focused on getting things accomplished that I kind of forget about the weight and tightness of the harness. I don't think anyone could ever feel completely "natural" with a tight harness strapped against their back, however, I have become accustomed to it. After I have been wearing my arm for a few hours or all day, my upper back and neck feel strained, tired, and sweaty, from the weight of the arm, and the tightness of the harness against my back. It also causes my left arm pit to feel irritated from the arm hole strap. It feels good to pull my arm off and just be "free" from the heavy arm and tight strap at the end of the day.

I understand completely why many above the elbow amputees refuse to wear a prosthetic arm. The harness is probably the biggest factor that affects my feelings. It is uncomfortable, and causes me to have upper back pain. I need on going massage therapy, and a heating pad on my back before bed to help deal with the irritated muscle pain. The weight of the arm I am sure contributes to this issue. There is no doubt that a lighter arm and no harness would influence my feelings of "my arm" being part of me.

The reactions from others, whether positive or negative, definitely effect how I feel. It took a huge amount of courage at first to go out in public, and feel confident using my arm. People are naturally curious, and there is a lot of starring. Over the last 2 years I have learned to ignore the starring most of the time, but the way people react can change the way I feel at that moment. Negative reactions make me feel objectified, and judged, and self conscious. Positive reactions make me feel accepted, normal, and comfortable, and definitely have an effect on my arm feeling a part of me.

I: Thanks very much for detailing how those factors can have an influence on your feelings. Do you think the amount of sensory feedback you receive from your prosthesis has any influence on your feelings towards it?

P: Yes, the sensory feedback I receive from my prosthesis definitely influences my feelings towards it. When I am doing tasks, I don't feel like I have to think hard about making it function. It feels like natural movement most of the time. It took lots of practice to learn how to control it at first. It was awkward, and frustrating at first. I would practice just opening and closing the hook, and rotating the wrist while I watched TV. Being able to control movements with my thought process is amazing. The sensory feedback is a huge contributor to feeling "a part of me" because it is uniquely me. My thoughts, my nerves, my muscles, and my prosthesis communicating, and working naturally together.

I: Thanks very much.

It is good to hear how the feedback from your thoughts and nerves to control your prosthesis influences your feelings towards it.

Thinking about the opposite direction of this process, in terms of any physical feeling you receive back from using your prosthesis (e.g., from moving the hand, touching an object), do you think this has any influence on you feeling your prosthesis as part of you?

P: When I am touching an object, I think of it as my real hand, and it feels like a part of me. In my mind I see my hand, and I can even feel my elbow, and wrist, whether I am using my prosthesis, or not wearing it as well. When I am using my prosthesis, it enhances that feeling of my real arm, because I am physically able to touch, and reach for objects. There have been a couple moments, when I have actually forgot about my missing limb, and dropped something, because my prosthesis isn't as accurate as I am seeing it or feeling it in my mind.

I: Thanks very much for detailing your experiences. You mentioned a few things of interest. Just to check, when you said you could feel your wrist did you mean feel

sensations from your missing arm (phantom limb sensations - where you experience your limb still being present)? If so, can you please describe any sensations you have and where your phantom limb is in relation to your prosthesis?

That is interesting that when using your prosthesis the feeling of your arm is increased. Just to clarify, is this just an increase in feeling your arm being present or both this and your prosthesis feeling part of you (i.e., it feeling even more part of you when you are touching objects)? Sorry if that is a difficult thing to answer!

That was also interesting to hear about an outcome of your prosthesis feeling part of you and, where you forget about it. Please let me know if I have misunderstood that though.

P: This is a hard one to explain. I think that it's more of my prosthesis feeling a part of me. I feel my phantom limb all the time, and it is so hard to explain how that feels in relation to my prosthesis. When I am using my prosthesis to touch objects, I feel my hand open and close (for example). I think that my brain has been trained to think about opening and closing my hand, and over time it has become so "natural", that I have briefly, forgot about my missing limb. I guess that I have just become really good at using thoughts, and the feeling of my phantom limb to make my prosthesis operate. When I first got my prosthesis, I thought this would be impossible to learn. I think it's kind of like being able to integrate my thoughts and the phantom sensations, and make the prosthesis move the way I need it to. I envision my missing limb doing the task.

As I am trying to explain this, I am amazed about how far I have come. I still have a lot of work to do though before I get my new TMR arm. I am currently doing TMR training.

I: Thanks for clarifying those aspects, especially as I appreciate it may be difficult to explain.

From what I understand you feel your phantom hand open and close when you control your prostheses. If so, it sounds like your phantom limb is spatially matched with your

prosthesis (i.e., in the "correct" position). Do you feel this helps your prosthesis to feel part of you? It's no problem if you are unsure but would be interested to hear your thoughts.

Also, do you have any phantom limb pain or any other specific sensations (aside from feeling your arm)? If so, please let me know if you feel these have any influence on your prosthesis feeling part of you (i.e., encouraging or diminishing this feeling, depending on what you experience).

Also, that is great to hear you feel positive about everything you have achieved.

P: I do think the proper placement of the electrode sites and having a well fit socket helps tremendously. I have had several fittings and adjustments, especially in the beginning. The "correct" positioning is a process, and takes time to get it right. The shape of my residual limb has changed over the last couple years, and the adjustments to the sites and socket are necessary. It definitely adds to making my prosthetic feeling a part of me when I am able to connect my thoughts (my phantom limb), and make the mechanical parts function.

I think that wearing my prosthetic arm helps with the phantom limb pain. I don't really think of it as "pain" anymore. It's more of a constant feeling of having an arm that's "asleep" (that tingly sensation, only 10 X more than normal). When I wear my arm, I don't really feel it as much, because I am focused on doing tasks. At night time when I am not wearing my arm, and I am relaxing, I usually experience "electrical shock" sensations shoot up my phantom limb. Or at times, I often feel like parts of my phantom limb "itch", and this can drive me crazy! The electrical shock sensations can sometimes be quite painful, but don't last long.

I: Thanks for detailing your thoughts. Apologies, but when I mentioned the "correct" position I meant in terms of where your phantom hand /arm is spatially compared to where your prosthesis is. So, for example some people can experience their phantom hand further back inside their residual limb, whereas others can feel it extending out from their residual limb in generally the same place as where their original arm was. I was interested to hear about where you can feel your phantom hand in relation to

where your prosthetic hand is and if this has any influence.

However, what you mentioned about having a well fit socket and the correct placement of electrodes is also of importance, so thanks. Is it possible to elaborate on why these two things encourage your prosthesis feeling part of you? I think you are suggesting this when you mentioned connecting your thoughts to make the mechanical parts function. If it helps, please consider a time when the positioning was not correct and how this impacted your feelings.

Thanks also for detailing your phantom limb sensations. It is good to hear wearing your prosthesis reduces these. Sorry if this is difficult to answer as you don't experience them much when wearing your prosthesis, but do you think the sensations have any influence over your feelings towards your prosthesis?

Sorry I meant to say previously, I hope your TMR training goes well.

P: I feel my phantom hand extended from my residual limb. I often visualize my "real" arm being there, but it feels shorter. This is hard to explain. I often try to explain this to friends and family, and know that they will never understand this unless they lose a limb. I think this does influence my feelings, because my prosthetic arm adds the function, and visualization of an arm.

When my socket has not fit well, or the placement of the electrodes is not right, it makes using my prosthetic a very frustrating experience. I have been at the grocery store, and could not open or close my hook or stop the wrist from spinning. I actually have just turned the arm off a couple times when I have had moments like this. At these times it has made me feel out of control, and it can be embarrassing. At those moments the prosthetic arm feels more like a tool that is broken and useless. It can be exhausting to try to get the arm to function when the socket is loose, and there isn't good contact with the electrode sites.

As for the phantom sensations that I do feel when wearing my arm, yes they do impact my feelings when I am able to make the prosthetic function with ease. When I



can feel my hand open in my thoughts, and the hook opens, it makes it feel like it's part of me.

I: Thanks very much for detailing the impact of your phantom limb sensations on your feelings towards your prosthesis.

Firstly, I'm sorry it has been difficult to explain, which is understandable and I have heard accounts from many others who experience their phantom arm shorter than their original arm.

OK, from what I understand, feeling your phantom limb and seeing your prosthesis helps to encourage the prosthesis to feel part of you, but your phantom arm being shorter does not have an influence (e.g., your phantom hand being in a different place than your prosthetic hand). Also, as you mentioned phantom sensations when wearing your arm, I assume your phantom limb pain (aside from feeling your phantom arm) has no overall influence on your feelings towards your prosthesis. Are those interpretations correct?

Thanks also for clarifying the temporary impact of both a loose socket and incorrect placement of electrodes on feelings towards your prosthesis.

As the above is just confirming I understand what you were mentioning, I next wanted to ask a potentially difficult question to think about, which relates to your body image (your conscious thoughts about your body) after amputation but before starting to use your prosthesis (if you can remember this time).

Do you think how you felt about your body (e.g., how positive or negative you felt about it) had any influence on your feelings towards your prosthesis? Apologies if this is difficult to think about.

P: Initially, after the amputation, I could not even look at my residual. I would turn my head to the left to avoid seeing it when doctors or nurses were changing the dressing, etc. Even though I felt grateful to be alive, and I knew I could live without an arm, it was hard to accept how different I looked. I avoided looking at the right side of my

body in mirrors. It took 3 weeks before I actually looked at my residual arm. It was scary and gross because it was covered with dark bloody scabs and stitches. At first the word "prosthetic" was foreign, and depressing to hear. I had always put a lot of effort into how I presented myself to the world. I have always enjoyed exercise, staying fit, dressing nice, and wearing makeup. Losing an arm dramatically had an effect on my self esteem. I had to re-learn how to put makeup on, and I had to use my teeth to twist open the mascara. I felt ugly, my residual arm was swollen and very large, and I had very limited function of my shoulder due to all the trauma and a fractured clavicle. I could not wear most of my clothes because of the swelling. Wearing anything with long sleeves was not an option. The thought of a prosthetic arm was scary. It was devastating to see the way my family and friends looked at me (I could see fear and sadness in their eyes). The stares from strangers made me feel uncomfortable. It was embarrassing at times.

After a few months of physical therapy, recovering from all the trauma, and adjusting to my new life as an amputee, I started to better accept my body. After meeting with my mentor, Carrie, and Ryan, my prosthetist, I felt more accepting, and more at ease about having a prosthetic arm. I was excited about all the new technology, and I was thinking that a prosthetic arm would make me look more "normal", especially when wearing long sleeves.

I definitely feel like my body image feelings have influenced the way I feel about my prosthetic. I still avoid looking at my right side in mirrors when I am not wearing my arm, but I feel more at ease looking in the mirror when I am wearing my arm. I feel better when I wear a long sleeve coat, even though sometimes people kind of "freak" out when they see a metal hook instead of a hand. As time has gone by, I have figured out my clothing options, the gym (getting exercise, and ways I can use my arm to help with exercise), and using my arm to help open the mascara. All these things have helped me with my body image, and influence my feelings towards my prosthetic.

I: Thanks very much for detailing your experiences relating to your body image especially with this covering some negative experiences. I would like to ask further about a few things you mentioned.

Just to check I understand correctly, do you mean that your negative feelings towards your body encouraged your prosthesis to feel part of you?

Did you also mean that figuring out your clothing options, using your prosthesis at the gym, and using it for opening your mascara has helped in your prosthesis feeling part of you? I was unsure if you meant that those things have separately helped improve your body image and also influenced feelings towards your prosthesis.

I was going to ask you about this later, but as you are discussing the connection between your body image and feelings towards your prosthesis in detail I wanted to ask if you feel there has also been an 'opposite' influence - does your feeling of your prosthesis being part of you have a subsequent effect on your body image (beyond simply wearing your prosthesis)?

Let me know if you are unsure about that and apologies if it is difficult to disentangle the effects of body image influencing feelings towards your prosthesis with the reverse.

P: I think that over time my feelings about my body image have improved because of all the positive ways my prosthetic arm has impacted my life. When I am wearing it, my body looks normal (somewhat) because it fills the space of the missing limb. My prosthetic arm fills out the long sleeved clothing items. It has also helped me regain the ability to do things, like opening my mascara, and doing planks at the gym. These are things that impact my body image. The negative body image feelings have been overcome partly because of all the positive impact. These are just a few examples of ways I feel my prosthetic has helped me overcome those negative body image feelings, and influenced my positive feelings towards my body image and my prosthetic.

The negative feelings did not influence or encourage my feelings about my prosthetic being part of me. If anything, the negative feelings influenced fear of wearing a prosthetic arm. I had to focus on ways a prosthetic arm could help improve my body image, and get my life back in the beginning. I had to get my mind set away from

seeing the prosthetic as a negative, and be open to embracing a different but "new" me with a prosthetic. I feel that my prosthetic has helped me regain some confidence in my body image, and in turn has influenced my feelings of my prosthetic being part of me.

I do think that beyond "simply wearing" my prosthetic, it has become part of me. I am not sure how to put this into words though. It's become a new part of me, even when I am not wearing it. I am proud of it. It looks just like the shape of my missing arm (a bit bulkier), and it makes me a very "unique" person as my prosthetist has told me.

This has been hard to explain, and has taken some time for me to think about. I hope you understand better what I have been trying to convey. I appreciate your patience when it takes time for me to "think" before answering the questions.

I: Thanks very much for detailing your feelings in depth and apologies this has been difficult to think about and explain. I do believe I understand what you were trying to convey. Just to summarise, my understanding is that you feel that specific things (as you mentioned) have both influenced your body image and feeling of your prosthesis being part of you separately, but that your body image has not influenced your feelings towards your prosthesis.

Also, to be clear, from what you said here - "I feel that my prosthetic has helped me regain some confidence in my body image, and in turn has influenced my feelings of my prosthetic being part of me." -

I interpret this as you meaning that it is aspects associated with your prosthesis (e.g., benefits it provides you with, as you mentioned) which help it to feel part of you, not that these have improved your body image, which has subsequently improved your feelings towards your prosthesis (i.e., not your body image influencing feelings towards your prosthesis). Hope that is correct!

Oh, I'm sorry, I meant something different when I said "simply wearing", not that whether your prosthesis has become part of you beyond simply wearing it. I have copied the part I said below -

"as you are discussing the connection between your body image and feelings towards your prosthesis in detail I wanted to ask if you feel there has also been an 'opposite' influence - does your feeling of your prosthesis being part of you have a subsequent effect on your body image (beyond simply wearing your prosthesis)?"

To clarify, what I meant is that simply wearing your prosthesis could encourage a feeling of improved body image, and I wanted to know if, on top of this, having your prosthesis feel part of you further influenced your body image. Hope I have explained that more clearly now, but please let me know if you think this has influenced your body image now.

However, I also want to respond to what you wrote. That is interesting to hear it still feels part of you when not wearing your prosthesis. As you mentioned the shape of it being similar to your missing arm and that it makes you a unique person (you may have talked about this previously but please do elaborate on this if happy to do so), would you say these are aspects which encouraged it to feel part of you? I believe that is what you were suggesting.

Thanks for everything you are sharing and look forward to hearing from you again.

P: My prosthetic has definitely influenced my feelings about my body image. I think I look better in photographs when I am wearing it for one thing. Also, I think the time I started wearing my prosthetic, was about the same time I was feeling more accepting or "at peace" with missing an arm. When I first got my prosthetic I was amazed at how much the shape looked like my missing arm. Even though at first I felt a lot of frustration while learning to use my prosthetic, I liked how I could wear a coat (long sleeves) and look more normal. I started feeling better about myself, and being out in public. When it is warmer out, and I don't need a coat, my prosthetic has become a conversation starter at times. My prosthetic has been customized with the word "LOVE" in gold lettering across the forearm, and I have some heart shaped rhinestones attached as well (see picture attached). Occasionally someone will ask me about it, or compliment my "tattoo" (the word "Love"). It represents my personality, and everything about it is uniquely me (the shape, size, and the way it works). It was made specifically for me.

The prosthetic is a bit longer than my missing arm though. I am petite, and because of the mechanics, it could not be made any smaller. The length from my shoulder to the elbow needs to be shorter. So the length of my prosthetic is awkward compared to my other arm. I am hoping with improvements in technology, I can someday get a lighter, and smaller prosthetic arm. I think getting a hand instead of a hook will also help with the length, and my body image.

I recently found out that the plans for my new TMR arm have changed because our insurance changed. The new policy does not "believe" in articulated hands. I was going to get a Bebionic extra small hand, and now I have to settle for a basic sensor hand for now. This is very disappointing for me. I think an articulating hand would open up even more opportunities for me. Hopefully the cost of technology will be improved as well so insurance will be willing to cover the cost. I think money is the real reason behind their reasoning.

I: Thanks very much for further explaining the influence of your prosthesis on your body image. Just to check so I don't misinterpret what you mentioned, would you say the feeling of your prosthesis being part of you also influences your body image (I mean in terms of how you think or feel about your body)?

Also, thanks for mentioning further about the individual aspects of your prosthesis (and it was nice to see a photo of this!). I recall from earlier you saying that being able to customise the appearance of your prosthesis helped encourage it feeling part of you. Would you say the similar shape to your missing also had an influence?

As these are things we have been discussing already I will include a new question here I don't believe I've asked you yet. We talked earlier about your feelings changing over time but have there been any specific times when your prosthesis has felt more or less a part of you (e.g., where your feeling towards your prosthesis temporarily changed)? If so, can you please describe what was happening and why you think it changed your feelings. It is no problem if you can't think of any specific moment or your feelings only changed gradually. Please let me know if you are unsure about this question.

I'm sorry to hear about the news on your TMR arm. I hope things change in the future so you can get the hand you want to have.

P: I do feel that my prosthetic arm has helped me feel better about my body. When I am wearing it and I am using it, I feel like I look better, and it makes me feel normal. Just being able to wear a coat without a "knotted" sleeve, and look normal has an influence on my body image and my prosthetic feeling part of me. The similar shape of my prosthetic arm compared with my missing limb influences this as well. When I first saw how much the shape looked like my missing arm, I felt better about body image, and more open to wearing a prosthetic arm. I recently found a picture of me taken a year prior to losing my arm, and was amazed at how much it looks like my missing arm (the shape).

My feelings do change at times regarding my prosthetic. If I am having a bad day with the way it fits, or trouble getting the hook or elbow to work I just want to take it off and forget about it for a while. For example; when I am cooking and need to hold a hot pan handle, but can't keep the hook to stay shut, it can cause some frustration. I had a hot pan full of melted chocolate that I spilled because I couldn't stop the hook from spinning. There have been times recently because my current socket is a bit loose (I have a silicone socket and I use hand sanitizer to get it on), and I have had trouble putting my prosthetic arm on because it slips off before I can get the harness on. Or when I am at the grocery store, and I am having to adjust the elbow constantly when pushing a shopping cart, and the hook keeps slipping off the shopping cart handle. Or when I am in public and negative reactions from people can make me feel bad. If I get frustrated with the fit or function, or negative reactions from people can influence how I feel. I definitely have some days when I need to take a break from my prosthetic. There are also days when it just feels "heavy" and my neck and shoulders hurt from the harness, and I have a hard time feeling comfortable wearing my arm. I often tell people that I have a love / hate relationship at times with my arm, depending on the day and circumstances.

I: Thanks for sharing your further thoughts. That is good to hear that wearing and using your prosthesis influences your body image. It may be tricky to think about this, but

does having your prosthesis feel part of you also contribute to this? As in, does feeling your prosthesis as part of you encourage positive feelings towards your body? Sorry if you have answered this but want to avoid misinterpreting how you feel.

Also, thanks for explaining in detail how your feelings can change temporarily. We have been discussing whether your feelings towards your prosthesis can influence your body image (depending on how you answer the above question), but in general does your feeling of your prosthesis not being part of you have any other particular outcomes for you? These could be either positive or negative outcomes. Please let me know if you are unsure about that question.

P: Yes, I do believe that my prosthesis feeling part of me does have a positive influence on my body image. When my day is spent getting lots of tasks completed and my arm is functioning and fitting well, I feel good about the way I look, and feel confident. When I am experiencing frustration with the fit or function, and have a temporary change in my feelings, I don't feel that it has any influence in regards to my body image, positive or negative. I just feel mad at my prosthetic.

What does influence some negative body image feelings, are bad reactions from people. I have experienced some discrimination, and rude behavior in general when wearing my prosthetic. The negative reactions can make me feel embarrassed about my prosthetic, and ugly, and have made me at times want to go out into the world without my prosthetic. I have found that I get the same reactions regardless of whether I am wearing my prosthetic or not though. I have to remind myself that people react out of "ignorance" or do not have any "filter", and that they just don't understand my circumstances. For example, I once wore my prosthetic to a dermatology appointment, and the doctor made a comment about how my prosthetic arm looked uncomfortable, and why would I want to wear it? I went from feeling proud about my prosthetic, to feeling very embarrassed for wearing it to my appointment. I avoided wearing it to my next appointment.

I: Thanks, so to summarise my understanding from what you said, with feeling your prosthesis as part of you this encourages you to feel more positive about your body but when you temporarily have a change in feelings (feeling less a part of you) this



does not then subsequently impact your body image?

This may be a subtle point but wanted to clarify my understanding further - would you say that your overall feeling of your prosthesis as part of you encourages feeling positive about your body overall, or rather that you have a temporary change in feelings towards your body? Sorry if that is unclear and let me know if you are unsure about this. I am particularly interested in whether your feelings have an overall influence on your body image or a temporary influence (was unsure if it was the latter as you mentioned about when your prosthesis is functioning well).

Thank you for sharing details of how negative reactions from people can affect your body image.

P: I think it's mainly when I encounter negative reactions to me and my prosthetic from people that cause my temporary feelings to change in regards to my body image. This has been difficult to explain. Most of the time I feel confident and at ease when wearing my prosthetic. I feel like it has helped me feel more confident about my body image overall, however, there are moments when a negative reaction (such as a rude comment) can make me feel bad about my body. I often feel "empowered" when wearing my prosthetic, and most of the time it feels just like part of me, and these feelings influence that confidence about my body image.

Yes, overall, my prosthetic feeling part of me, definitely encourages a positive feeling about my body image.

I: Thanks very much and sorry it has been difficult to explain but I think you explained things well.

I don't think I have asked you this before (please let me know if you have discussed this already) but do you think you use your prosthesis more because it feels part of you? If this is difficult to think about imagine your prosthesis did not feel part of you, and whether you think you would use it less as a result of this feeling.

P: I don't think I would use my prosthetic much at all, if I didn't feel that it was part of me. When I first got "my arm", it felt awkward and very foreign, and I felt anxious and afraid to wear it, especially out in public. Getting it to function was very frustrating at first. It did not feel part of me in the beginning. I have heard about many amputees going home with their prosthesis, trying to use it a couple of times, and then throwing it in a closet. For me, it took time to become part of me. I stuck to a schedule of gradually wearing my prosthesis for longer periods over a couple months. The more I wore it and used it, the more it felt like part of me. I think that many amputees, (the non-prosthetic users), haven't allowed enough time learning how to use a prosthetic before giving up. I think it takes time wearing and using a prosthetic before it feels part of you. A person needs to be open to dedicating time to wearing a prosthetic, and understanding that it will take time to learn how to use it. Getting to that feeling of being part of me took time, and I don't think I would be a prosthetic user today, if I had not allowed myself to be open to the process of learning to use and wear a prosthetic.

I: Thanks for detailing how your feelings towards your prosthesis have influenced your use of it. Also, further mentioning your experiences in getting used to using your prosthesis. Relating to use of your prosthesis, do you think feeling your prosthesis as part of you influences how well you can perform activities with it? Please let me know if you are unsure of that.

P: Yes, my feeling of my prosthetic being part of me definitely influences my confidence level and my ability to perform activities with it. It took hours of practice doing simple tasks, and learning to control functions "naturally". The "natural" rhythm of movement and control has increased over time, and this has made doing activities easier. At first for example, it was difficult to handle plastic produce bags at the grocery store because it felt awkward being in public with my prosthetic, and there was frustration with learning to control it. The more time spent wearing "my arm" has influenced the feeling of being part of me, and also my ability to perform activities with it.

I: Thanks for this, I am particularly interested in how your prosthesis feeling part of you increases your confidence and ability in performing activities. Just to check, is the

natural control of your prosthesis encouraged by the feeling of your prosthesis as part of you on top of/as well as the amount of time spent using it?

Also, does such feelings have any influence on your awareness of your prosthesis (e.g. Make you more or less aware of it)? We discussed earlier how your limited conscious awareness of your prosthesis encouraged it feeling part of you, but I am interested in whether your feelings towards your prosthesis have a similar effect on your awareness or not. Let me know if unsure about that.

P: I think that the more time I spend wearing my prosthesis has influenced my confidence and ability to perform activities, because overtime the movements feel more "normal". The more I wear my prosthesis, the less I have to think about navigating tasks, and I think I become less aware of the prosthesis. I get a more "natural" rhythm going and don't really think my prosthesis. I definitely feel that the combination of time spent wearing it, and my ability to make it function without having to think contribute to my prosthesis feeling part of me. Practice and lots of patience are a requirement when learning to use a prosthesis. Once I mastered the functioning part, it became easier, more natural feeling, and it has had a direct influence on my confidence and awareness levels.

I: Thanks very much, that is great to hear how time using your prosthesis increases your ability in performing activities, and reducing your awareness. Would you say that having your prosthesis feel part of you also has one or both of these outcomes? As in, aside from amount of use, does the feeling of being part of your increase your ability with and/or reduce your awareness of your prosthesis?

Would you say feeling your prosthesis as part of you had an influence on your overall satisfaction with your prosthesis? To clarify this, I mean whether feeling your prosthesis as being part of you had an impact on either increasing or decreasing your general satisfaction with your prosthesis?

Apologies if we have discussed this previously, but do you have a desire or need for your prosthesis to feel part of you? We have discussed about your prosthesis feeling

part of you, but this is asking if this is something you enjoy having for whatever reason.

P: My prosthesis feeling part of me definitely influences both my ability to use it, and my awareness of it. When I am having a very productive day and managing to get it to function well, my awareness of it lessens. I do think aside from the use of it, just having it feel a part of me influences both function and awareness. Also, the way my prosthesis feels does determine my satisfaction level. If I have a bad day for example; a day when it's not fitting well, I just want to take it off. I do have days when it feels heavy and my shoulders and neck hurt from the harness. On these days I don't feel like it is part of me and I don't feel like wearing it very much.

I definitely do have a desire for my prosthesis to feel a part of me. I really feel that it takes a positive attitude, desire, and acceptance to wear a prosthetic. I am willing to find a way to use "my arm" to make my life better. There are many positive and negative things about prosthetics, but I choose to focus on the positive. I have worked hard at making a prosthetic arm part of the "new" normal for me.

I: Thanks very much for your email, from what you mentioned my understanding is that when your prosthesis functions well this reduces your awareness of it, but also your feeling of your prosthesis being part of you affects both of these aspects overall (i.e., being part of you encourages your ability in using your prosthesis and reduces how much conscious awareness you have of your prosthesis overall). You are less satisfied with your prosthesis at times when it does not fit well, and this also makes your prosthesis feel less part of you. Lastly that you have taken steps or have a state of mind towards your prosthesis to encourage it feeling part of you.

Following the above and to clarify these final areas, beyond temporary effects on your satisfaction (e.g., it fitting well) does your feeling of your prosthesis being part of you have an influence on how satisfied you are with your prosthesis overall (e.g., does this feeling alone make you more or less satisfied with your prosthesis)? Secondly, is the feeling of your prosthesis as part of you a positive thing (i.e., is this something you enjoy or are happy to experience?).

P: The feeling of my prosthesis being part of me is very positive for me, and it definitely influences how satisfied I feel overall. Beyond any temporary changes that effect my satisfaction level, I enjoy the feeling that it is part of me. I feel very proud about being a successful prosthetic user, and having that feeling that it is "part of me" definitely makes me feel more satisfied with my prosthetic.

I finally got my TMR arm. I really wanted a Be-BIONIC articulating hand, but the insurance would not cover it, so I have a sensor hand. Not sure it really is better than my hook yet, other than it looks like a real hand. I have had some frustrating moments learning to control and differentiate each function, but the electronic elbow makes it feel even more like it's part of me.

I: Thanks very much for explaining the positive aspects of feeling your prosthesis as part of you, and how this feeling increases your overall satisfaction with your prosthesis. It is good to hear your positive outlook on your experiences.

Great to hear you have received your TMR arm but sorry it is not the one you wanted. Interesting to hear how the electronic elbow makes this feel even more a part of you. Is that because you can think of bending your arm at the elbow and then it moves accordingly? Also, as you mentioned the hand compared to a hook, do you think this has any impact on how much it feels part of you (e.g., in terms of its appearance or functionality)? No problem if you have not used it long enough to be able to differentiate the impact of these on your feelings.

However, to check, is there anything else you wanted to add to the interview which you think would be important to mention for this specific area? No problem if you don't wish to add anything as you have shared a lot, just let me know and I shall send you some final information if happy to complete the interview.

P: Yes, I do think that the electronic elbow does feel more a part of me due to the fact that I have to think about bending my arm to make it function. The hand looks like a real hand, but functions more a hook only it's bulkier, and the fingers don't move. I really think I haven't had it long enough to really decide how I really feel about the

hand yet though. Also, I don't have a wrist yet, so it really doesn't function as well as I would like it to at this point. I am still learning to differentiate open / close and the up / down function.

The most important thing I have learned about wearing a prosthetic, is that it's a long process, and requires a lot of patience and practice. I believe that it requires a lot of time practicing using it, and the more you wear it the better. I think a person has to have a positive attitude and be open to trying and making a commitment to wearing a prosthetic, especially when learning to use one. I am a person that never gives up, and my prosthetist has pushed me hard as well, and I think this has helped me to be a successful prosthetic user. I clearly know how much more functional my life is because of my prosthetic, and I am grateful to have it.

I: Thanks very much for your thoughts on those points that is really useful to hear about. Also, of course, that is completely understandable you have not had your hand long enough to make a direct comparison with your previous hook yet, but thanks for considering this.

Also, thanks for sharing your final thoughts on your overall experience of your prosthesis and the approach you have taken to maximising your success with this.

Overall, thanks very much for sharing your experiences for my research which I really appreciate. I am happy you have enjoyed the interview and hope you found it interesting, and the information you have shared has been really useful. No need to say thanks for my patience, the thanks is all mine to give you for your involvement!

P: I don't have any questions, I enjoyed participating in this study, and actually learned a few things about myself! It really made me think about how far I have come in 3 years as an amputee.

## Appendix J: Ethics application approval for survey study



Research, Enterprise and Engagement  
Ethical Approval Panel

Doctoral & Research Support  
Research and Knowledge Exchange,  
Room 827, Maxwell Building,  
University of Salford,  
Manchester  
M5 4WT

T +44(0)161 295 2280

[www.salford.ac.uk](http://www.salford.ac.uk)

8 October 2018

Dear Andrew,

**RE: ETHICS APPLICATION–HSR1718-121 – ‘An exploration of factors associated with embodiment of upper limb prostheses.’**

Based on the information that you have provided, I am pleased to inform you that ethics application HSR1718-121 has been approved.

If there are any changes to the project and/or its methodology, then please inform the Panel as soon as possible by contacting [Health-ResearchEthics@salford.ac.uk](mailto:Health-ResearchEthics@salford.ac.uk)

Yours sincerely,

A handwritten signature in black ink, appearing to read 'Sue McAndrew'.

Professor Sue McAndrew  
Chair of the Research Ethics Panel

**Appendix K: Introductory email, poster and twitter advertisements, and sources  
contacted for survey study**

**K.1 Introductory email to send to sources**

Email subject - Request to advertise PhD prosthesis embodiment research study (University of Salford)

School of Health Sciences,  
Allerton Building,  
University of Salford,  
Salford,  
Manchester,  
M6 6PU

Dear Sir or Madam,

My name is Andrew Hodrien and I am a PhD researcher from the School of Health Sciences at the University of Salford (Manchester, UK) conducting research with people who have lost an upper limb through amputation and people with congenital upper limb absence. My research is entitled ‘An exploration of factors associated with embodiment of upper limb prostheses’. Prosthesis embodiment is a term used to describe the feeling that a prosthetic limb is a ‘part of’ the user.

In my previous interviews study with prosthesis users I identified a large range of potential factors which may be associated with upper limb prosthesis embodiment. This study aims to further explore these factors in a larger sample via questionnaire, to quantitatively measure their association with embodiment. The information gained is hoped to inform prosthetics design and/or rehabilitation.

Please could you post a small advertisement of the study on my behalf to your readers on your website, any social media accounts you have (e.g., Facebook and Twitter), and/or sent to



members if you have a mailing list or newsletter, for your readers to hear about the research, which may be of interest to them. Also, if there is anywhere else suitable you would be happy to post it to.

The research involves completion of an anonymous self-contained online survey which takes about 30-40 minutes to complete. The survey questions cover background on the user and their prosthesis, followed by questions on feelings towards their prosthesis. The study has been assessed by the University of Salford's ethics committee and follows the research code of The British Psychological Society.

Please see the attached advert (and separate smaller advert for Twitter, if appropriate) to post which includes a link to the self-contained survey. Full information is provided from the link including my contact details if a potential participant has any questions (otherwise they don't need contact myself).

I am recruiting until the 24/03/19 and am aiming to recruit as many participants as possible for this final study in my PhD, so I would appreciate any support.

If it is not too much trouble could you please let me know if you decide to post the advert and let me know where it gets posted (so I can monitor the various places I am recruiting from)?

Many thanks in advance.

Yours sincerely/faithfully,

Andrew Hodrien

## **K.2 Poster for survey study advertisement**

### **Have you been using an upper limb prosthesis? - Research participation request**

If so, we are interested to hear from you about your experiences of this and participate in research from the University of Salford – ‘*An exploration of factors associated with embodiment of upper limb prostheses*’.

The aim of this study is to explore whether specific factors are associated with upper limb prosthesis embodiment (the feeling of the prosthesis being ‘part of’ you). We hope this will develop understanding of prosthesis embodiment and have important implications for prosthetic design and/or rehabilitation.

The research involves completion of a short anonymous online survey, covering a range of feelings towards your prosthesis along with some background questions.

We hope to hear from anyone who is 18 or above and who has an upper-limb prosthesis.

Please follow this link to a survey detailing full information for you to read and decide if you wish to participate.

**Recruitment from 23/10/18 to 24/03/19 –**

[https://salford.onlinesurveys.ac.uk/factors\\_associated\\_with\\_embodiment\\_of\\_upper\\_limb\\_prostheses](https://salford.onlinesurveys.ac.uk/factors_associated_with_embodiment_of_upper_limb_prostheses)

Many thanks,

Andrew Hodrien (PhD researcher)

### **K.3 Twitter advertisement for survey study**

Have you been using an upper limb prosthesis? – Research participation request (until 24/03/19). Please see Andrew Hodrien’s PhD research (University of Salford) on prosthesis embodiment by following this link to an anonymous online survey – [https://salford.onlinesurveys.ac.uk/factors\\_associated\\_with\\_embodiment\\_of\\_upper\\_limb\\_protheses](https://salford.onlinesurveys.ac.uk/factors_associated_with_embodiment_of_upper_limb_protheses)

### **K.4 Sources contacted for survey study**

Table K1

*Summary of 261 sources contacted to advertise the survey study and outcomes*

Sources ( <i>N</i> = 261)	<i>n</i>
Replied	51
Supported	46
Social Media	31
Forum	7
Website News	8
Newsletter	2
Magazine	0

*Note:* Supported = said they would be happy to support the research or I noticed they posted the advert.

## **Appendix L: PIS, Consent form and instructions for completion for survey study**

### **L.1 Participant information sheet**

Page 1: PARTICIPANT INFORMATION SHEET (version 2 - 27/09/18)

Title of study: An exploration of factors associated with embodiment of upper limb prostheses.

Name of Researcher: Andrew Hodrien.

#### 1. Invitation paragraph

Thank you for taking the time to find out more about this research study. To consider if you wish to participate in the research please read the information below detailing why you have been invited, what will be involved, and how the study is being managed. If you wish to find out any further details please contact me on the email address at the bottom.

#### 2. What is the purpose of the study?

Some prosthesis users report that they experience their prosthetic limb as a part of their body, whilst others do not. This experience is known as 'prosthesis embodiment'. A previous interview study with prosthesis users identified a large range of potential factors which may be associated with upper limb prosthesis embodiment. The current study will aim to further explore 'embodiment' in a larger sample of prosthesis users. The information gained is hoped to help us understand what helps people with limb loss to accept their prosthetic limb, which may in the future inform prosthesis design or approaches to rehabilitation.

#### 3. Why have I been invited to take part?

We are inviting anyone over the age of 18, who has had the experience of using an upper limb prosthesis.

#### 4. Do I have to take part?

No, this is a completely voluntary study and it is up to you to decide if you wish to participate once you have read all the information. Please take at least 24 hours to consider your involvement. Taking the time to read all of the information provided about the study will help

you come to an informed decision. If you do wish to participate you will be asked to complete a consent form before completing the survey. However, anytime during the study you will be able to withdraw (without giving a reason) if you later decide you no longer wish to be involved.

5. What will happen to me if I take part?

Once you complete the electronic Consent Form you will be given instructions on how to complete the survey. You will then be asked to complete some background information about your prosthesis, including what type of device it is and how long you have had it. Following on from these questions, you will be invited to comment on whether or not you experience phantom limb sensations. You will then be asked to complete questions on your feelings towards your prosthesis. At the end you will be asked if you are happy for your data to be included in the study

6. Expenses and payments?

The research will be entirely voluntary so you will not be paid for your participation in the study.

7. What are the possible disadvantages and risks of taking part?

We understand that issues around the use of prosthetic limb could be of a sensitive nature so thinking about this may be difficult for you. However, if any particular question is uncomfortable to think about you do not need to answer it. If you wish to withdraw from the study, you can do so at any time without giving reason. If you wish to withdraw your data after the study is complete, you can email the researcher, providing your participant number generated in the survey (this is a unique 'receipt number' provided to you once the survey is complete), and request your data is removed. The final date for removal is 18/02/2019.

8. What are the possible benefits of taking part?

We cannot guarantee that you will benefit from taking part in this study, but it is hoped that the knowledge generated will ultimately help to improve how professionals, such as prosthetists and medical doctors, approach upper limb amputee rehabilitation and/or prosthetic design.

9. What if there is a problem?

If you have a concern about any aspect of this study, you should ask to speak to the researcher (Andrew Hodrien – Email: [a.d.hodrien@edu.salford.ac.uk](mailto:a.d.hodrien@edu.salford.ac.uk)) who will do their best to answer your questions. If you remain unhappy and wish to complain formally you can do this by contacting the Research Supervisor (Dr Adam Galpin - Telephone: 0161 295 7146). If the matter is still not resolved, please forward your concerns to Professor Susan McAndrew, Chair of the Health Research Ethical Approval Panel, Room MS1.91, Mary Seacole Building, Frederick Road Campus, University of Salford, Salford, M6 6PU, UK. Tel: 0161 295 2778. Email: [s.mcandrew@salford.ac.uk](mailto:s.mcandrew@salford.ac.uk).

10. Will my taking part in the study be kept confidential?

Your identity will be kept confidential by completing the survey anonymously.

11. What will happen if I don't carry on with the study?

If you decide not to carry on with the study you can provide your research code and then your data will be deleted. This can be done up until 18/02/2019 when the data will be written up and analysed.

12. What will happen to the results of the research study?

The results will be disseminated through the researcher's PhD thesis, along with publications and/or presentations in academic journal articles and conferences. These outputs will present the grouped results from all participants, and possibly any quotes where you wish to clarify your answer. These will be anonymous so it is unlikely that individual responses will be reported.

13. Who is organising or sponsoring the research?

The research is being organised by the Centre for Health Sciences Research, University of Salford, Salford, M6 6PU, UK. The research is being conducted as part of a PhD project funded by the University of Salford.

14. Further information and contact details:

If you would like to enquire about any additional information please contact Andrew Hodrien at [a.d.hodrien@edu.salford.ac.uk](mailto:a.d.hodrien@edu.salford.ac.uk)

Supervised by Dr. Adam Galpin. Email: [A.J.Galpin@salford.ac.uk](mailto:A.J.Galpin@salford.ac.uk). Telephone: 0161 295 7146. Senior Lecturer, School of Health Sciences, L812b Allerton Building, University of Salford, Salford, Manchester, M6 6PU, UK.

If you wish to seek support or further information relevant to your circumstances or experiences then I will provide here the contact details of amputee/prosthesis associations and a general support organisation:

The limbless association: [www.limbless-association.org/](http://www.limbless-association.org/) - for general advice.

Limbpower: [www.limbpower.com](http://www.limbpower.com) – for general advice or activities.

The British Limbless ex-servicemen's association: <https://blesma.org/> - if you have served in the British military.

Samaritans: <https://www.samaritans.org/> - for general support.

Thank you for taking the time to read about this study and for considering participation.

## L.2 Consent form

Page 2: CONSENT FORM

Title of study: An exploration of factors associated with embodiment of upper limb prostheses.

Name of Researcher: Andrew Hodrien

Please complete this form after you have read and understood the study information sheet.

1. I confirm that I have read and understand the study information sheet version 2, dated 27/09/18, for the above study.

I have had the opportunity to consider the information and to ask questions

Which have been answered satisfactorily. Required

Yes

2. I understand that my participation is voluntary and that I am free to withdraw at any time, without giving any reason, and without my rights being affected. Required

Yes

3.If I do decide to withdraw, I understand that the information I have given, up to the point of withdrawal, will not be used in the research. The timeframe for withdrawal is until 18/02/2019. Required

Yes

4.I understand that my personal details will be kept confidential and will not be revealed to people outside the research team. Required

Yes

5.I understand that my anonymised data will be used in the researcher's PhD thesis, along with publications and/or presentations in academic journal articles and conferences. Required

Yes

6.I agree to take part in the study by completing an online survey. Required

Yes



### **L.3 Instructions for completing the survey**

#### Page 3: INSTRUCTIONS FOR COMPLETING THE SURVEY

In the following survey you will be asked for general background information, details of your limb absence, details of your prosthesis use, along with specific feelings towards your prosthesis. You may own multiple prostheses (of the same or different type), but in answering relevant questions please only consider the prosthesis you wear for the most time in an average week, or if you have stopped using your prosthesis pick the one you used to wear the most.

For those with limb absence or use/used a prosthesis on one side: Please answer the questions based on the prosthesis used for this arm.

For those with limb absence on both sides and use/used a prosthesis on each side: Please answer the questions based on the prosthesis you most commonly wear/used to wear on your previous dominant hand (i.e., the hand you were most skilled at in tasks and favoured towards using, such as writing). If you have a congenital limb absence, or consider yourself to be ambidextrous (you could use both hands equally), pick whichever arm you feel you use the most.

Please contact the researcher if you are unsure of these instructions –

Andrew Hodrien: [a.d.hodrien@edu.salford.ac.uk](mailto:a.d.hodrien@edu.salford.ac.uk)

## **Appendix M: Items measuring embodiment and factors associated with embodiment**

### **M.1 Items measuring embodiment**

21. To what extent does your prosthesis feel part of you/your 'self' (self is defined as your sense of personal identity and of who you are as an individual)?

Not at all to Entirely

22. To what extent do you feel that your prosthesis is a part of your physical body?

Not at all to Entirely

23. To what extent do you feel your prosthesis is incorporated into your body image (your conscious thoughts and feelings about your body)?

Not at all to Entirely

24. To what extent do you feel a sense of ownership over your prosthesis (i.e., it feels like it is your arm)?

Not at all to Entirely

25. Do you have a habit of unintentionally touching your prosthesis?

Never to Always

26. Do you feel that, when something touches your prosthesis, it touches your body?

Never to Always

27. To what extent can you perceive the orientation and location of your prosthesis with your eyes closed?

Not at all to Very accurately

28. How quickly do you move your prosthesis when you intend to move it? Information: If body-powered or myoelectric, answer based on the moving parts. If cosmetic, answer based on the whole device.

Extremely slow to Very fast

29. How accurately can you move your prosthesis? Information: If body-powered or myoelectric, answer based on the moving parts. If cosmetic, answer based on the whole device.

Not accurately at all to Extremely accurately

30. How difficult is it to move your prosthesis? Information: If body-powered or myoelectric, answer based on the moving parts. If cosmetic, answer based on the whole device.

Extremely difficult to Extremely easy

31. To what extent do you feel a sense of agency over your prosthesis (i.e., that you are in control of the movement of your prosthesis)?

Not at all to Entirely

## **M.2 Factors associated with embodiment**

16. Please note whether your prosthesis has been personally customised. Customisation means you or someone on your behalf has specifically altered the visual appearance of the prosthesis.

17. Please select an appropriate response for how much you use your prosthesis in an average day.

18. Phantom limb sensations are defined as some feeling of your missing hand or arm as if it is present. Please indicate if you have experienced any phantom limb sensations at some point.

18.a. Have you experienced phantom limb sensations at some point during use of your currently most worn prosthesis?

19. If you have experienced phantom sensations have they caused you any pain? NB. This does not include non-painful sensations e.g., tingling or itchy sensations.

19.a. Have you experienced pain at some point during use of your currently most worn prosthesis?

20. Do your phantom limb sensations correspond with the position of your prosthesis? Please answer in relation to the prosthesis you consider your currently most worn.

32. To what extent do you have a desire or need for your prosthesis to feel part of you?  
Not at all to Entirely

33. Have your feelings towards your prosthesis (in terms of whether it feels part of you) changed over long periods of time? Information: This means did you notice your feelings changing gradually?

Not at all to Entirely

34. Have your feelings towards your prosthesis (in terms of whether it feels part of you) changed temporarily? Information: This means have you noticed your feelings changing for a short period of time before returning to how they usually feel (e.g., feeling more part of you, or less part of you, for a temporary period of time)?

Not at all to Entirely

35. To what extent do you feel an emotional connection to your prosthesis?

Not at all to Entirely

36. To what extent does your prosthesis feel unnatural or foreign?

Not at all to Entirely

37. Would you describe your feelings towards your prosthesis as similar to wearing glasses, shoes, or some similar object worn on the body?

Not at all to Entirely

38. Would you describe your prosthesis as feeling indispensable (i.e., you would feel incomplete if you had to lose it)?

Not at all to Entirely

39. How does control of your prosthesis feel?

Not natural at all to Very natural

40. How satisfied are you with the functionality of your prosthesis?

Not satisfied at all to Very satisfied

41. How satisfied are you with the appearance of your prosthesis?

Not satisfied at all to Very satisfied

42. How satisfied are you with how well your prosthesis fits?

Not satisfied at all to Very satisfied

43. How satisfied are you with the comfort/weight of your prosthesis?

Not satisfied at all to Very satisfied

44. How satisfied are you with the robustness of your prosthesis?

Not satisfied at all to Very satisfied

45. How satisfied are you with the speed at which your prosthesis responds to your intention to move it? Information: If body-powered or myoelectric, answer based on the moving parts. If cosmetic, answer based on the whole device.

Not satisfied at all to Very satisfied

46. How satisfied are you with the reliability of your prosthesis?

Not satisfied at all to Very satisfied

47. How satisfied are you with the noise of your prosthesis?

Not satisfied at all to Very satisfied

48. How satisfied are you overall with your prosthesis?

Not satisfied at all to Very satisfied

49. How skilled do you feel you are in using your prosthesis?

Not skilled at all to Very skilled

50. How many benefits do you think your prosthesis provides you with?

No benefits at all to A lot of benefits

51. How much sensory feedback do you receive from your prosthesis? Information: This could include specific sounds, feedback on your stump or other body part.

No sensory feedback at all to A lot of sensory feedback

52. To what degree are you consciously aware of your prosthesis when wearing in general or performing activities?

Usually no awareness at all to Often a lot of awareness

53. For unfamiliar tasks, how much planning do you feel like you need to do to perform the task with your prosthesis?

No planning to A lot of planning

54. How satisfied are you with your body image (your conscious thoughts and feelings about your body)?

Not satisfied at all to Very satisfied

55. How much negative attention are you aware of receiving from others as a result of wearing your prosthesis?

No negative attention to A lot of negative attention

56. How determined were you to succeed during initial training to use your prosthesis?

Not positive at all to Very positive

## **Appendix N: Debrief sheet for survey study**

### **Debrief Sheet**

**Title of study:** An exploration of factors associated with embodiment of upper limb prostheses.

**Name of Researcher: Andrew Hodrien**

Thank you for taking the time to participate in our research and share your experiences. These will be used to explore prosthesis embodiment, the prosthesis being ‘part of’ the user, identified by how you answered a range of questions in the survey. Additional questions you answered attempt to capture potential predictors of embodiment (i.e., encouraging or diminishing the likelihood of this occurring) which were previously identified in an in-depth qualitative interviews study with prosthesis users. The relationships between these potential predictors and embodiment will be explored to identify which are present and have the strongest relationship. The findings will hopefully both develop greater understanding of prosthesis embodiment and also inform prosthesis design and/or rehabilitation.

If you wish to seek support or further information relevant to your circumstances or experiences then I will provide here the contact details of amputee/prosthesis associations and a general support organisation:

**The limbless association:** [www.limbless-association.org/](http://www.limbless-association.org/) - for general advice.

**Amputee Coalition:** <https://www.amputee-coalition.org/> - for general advice and support information.

**Limbpower:** [www.limbpower.com](http://www.limbpower.com) – for general advice or activities.

**The British Limbless ex-servicemen's association:** <https://blesma.org/> - if you have served in the British military.

**Samaritans:** <https://www.samaritans.org/> - for general support.

We hope your experience of the questionnaire has been comfortable for you, however if through discussing sensitive experiences you feel upset about this you could enquire about counselling services by contacting your GP or your limb centre (if applicable), or contacting the NHS helpline on free telephone number 111 for further advice (or your equivalent doctor/health service, if not based in the UK).

If you wish to withdraw your data from the study can you please contact the researcher and provide him with your unique participant number generated in the survey (this is a unique 'receipt number' shown on your completion receipt once the survey is complete) and then he will remove your data. This can be done up until the end of 24/03/19.

If you have contacted the researcher directly your emails and contact details will be deleted once the research phase has been completed (25/03/2019). However, if you wish to be contacted by the Centre for Health Sciences Research at the University of Salford about future studies relevant to you, please read the following information: <http://www.salford.ac.uk/research/health-sciences/research-groups/research-participant-register>.

If you know anyone else relevant to this study who you think might be interested to hear about it or consider participating please pass on the survey link to them (or you can refer them to the place where you saw the original advertisement). If you are in contact with any potential further sources of recruitment (e.g., societies, forums, blogs, social media groups) and are happy to pass on the advertisement or survey link to them (or simply suggest to me) please let me know the name of them (in case I need to follow up any contact with them), thanks.

Many thanks again for your time participating in our research.

For any further information or to request withdrawal from the study contact –

Andrew Hodrien: [a.d.hodrien@edu.salford.ac.uk](mailto:a.d.hodrien@edu.salford.ac.uk)

Supervised by Dr Adam Galpin. Email: [A.J.Galpin@salford.ac.uk](mailto:A.J.Galpin@salford.ac.uk). Telephone: 0161 295 7146. Senior Lecturer, School of Health Sciences, L812b Allerton Building, University of Salford, Salford, Manchester, M6 6PU, UK.



## Appendix O: Ethical approval for VR study



Research, Innovation and Academic  
Engagement Ethical Approval Panel

Research Centres Support Team  
G0.3 Jouble House  
University of Salford  
M5 4WT

T +44(0)161 295 2280

[www.salford.ac.uk/](http://www.salford.ac.uk/)

2 May 2017

Dear Andrew,

**RE: ETHICS APPLICATION-HSR1617-116-'Exploring the impact of hand movement delays and hand appearance on myoelectric prosthesis embodiment using Immersive Virtual Reality.'**

Based on the information you provided I am pleased to inform you that application HSR1617-116 has been approved.

If there are any changes to the project and/or its methodology, then please inform the Panel as soon as possible by contacting [Health-ResearchEthics@salford.ac.uk](mailto:Health-ResearchEthics@salford.ac.uk)

Yours sincerely,

A handwritten signature in black ink, appearing to read 'Sue McAndrew'.

Sue McAndrew  
Chair of the Research Ethics Panel

## **Appendix P: Participant recruitment email and poster for VR study**

### **P.1 Participant recruitment email**

#### **Participant recruitment introduction email**

Andrew Hodrien, a PhD student from Health Sciences is looking for participants in his experiments on Virtual Reality and Prostheses. Please see the attached study poster to see if you are potentially interested in participating, which includes contact details for Andrew Hodrien.

# Experiencing a Prosthesis in Virtual Reality

Would you like to participate in an Immersive Virtual Reality experiment, experiencing controlling a virtual prosthesis?



We are looking for participants for a PhD study who are not upper limb prosthesis users from  
27/11/17 until 31/01/18

**Study aim:** To explore the experience of a prosthetic arm in virtual reality.

**The experiment:** Wearing a head-mounted Virtual Reality display whilst controlling a real and virtual prosthetic arm.

**For full information of the study please contact Andrew Hodrien**

Andrew Hodrien (PhD researcher) – [a.d.hodrien@edu.salford.ac.uk](mailto:a.d.hodrien@edu.salford.ac.uk)

Main supervisor – Adam Galpin ([a.j.galpin@salford.ac.uk](mailto:a.j.galpin@salford.ac.uk),

Tel: 0161 295 7146).

## Appendix Q: PIS, consent form and debrief sheet for VR study

### Q.1 Participant information sheet



#### Participant Information Sheet (Version 1 24/10/17)

**Title of study:** Exploring the impact of control method on experience of a prosthesis within Immersive Virtual Reality

**Name of Researcher:** Andrew Hodrien

Thank you for taking the time to find out more about this research study. To consider if you wish to participate in the research please read the below information detailing why you have been invited, what will be involved, and how the study is being managed. If you wish to find out any further details please contact me on the email address at the bottom.

#### **What is the purpose of this study?**

Some prosthesis users report that they experience their prosthetic limb as a part of their body, whilst others do not. Upper-limb electrically controlled (myoelectric) prostheses are controlled using arm muscles which may influence this process. The aim of this study is to explore the relative impact of this control method. This will be explored through a Virtual Reality simulation of a prosthesis combined with a control method similar to how myoelectric prostheses are controlled for one condition, and normal hand movement for another condition. You are being invited to participate in this study with the aim of testing various control methods.

#### **Why have I been invited to take part?**

We are inviting anyone over the age of 18, who is not an upper-limb prosthesis user, not previously felt sick experiencing virtual reality or 3D cinema, experience motion sickness,

regularly have migraines, or suffer from epilepsy. If you are unsure about any of these please discuss with the researcher.

### **Do I have to take part?**

No, this is a completely voluntary study and it is up to you to decide if you wish to participate once you have read all the information. Take at least 24 hours to consider your involvement. If you do wish to participate you will complete a consent form but anytime during the study you will be able to withdraw (with no given reason) if you later decide you no longer wish to be involved.

It is entirely up to you whether to take part. Taking the time to read all of the information provided about the study will help you come to an informed decision. If you decide to participate, you will be asked to complete and sign a consent form. Remember, however that if at any time during the study you decide you no longer wish to participate, you can withdraw or end your participation without needing to give a reason.

### **What will happen to me if I take part?**

Once you email me to confirm your interest in participating, I will email you an electronic consent form to complete and email back to me (or I can provide you with a consent form to fill out by hand when we meet if you prefer). We will then schedule a suitable time to meet at a lab in Allerton building, University of Salford. The whole experiment will last approximately up to 1 hour. Once at the room electrodes (Figure 1) will be attached to two of your fingers of your left hand (just with Velcro straps) which measure a physiological response to visual stimuli presented during the experiment recorded by a Biopac MP36 device (Figure 2). The electrodes will have a small amount of electrolyte gel placed on them which will make contact with your skin, however this can be wiped off easily. You will be asked not to wear hand cream before the experiment as this could interact with the electrode recording. You will also need to be able to remove any rings worn on your first and third finger of your left hand.

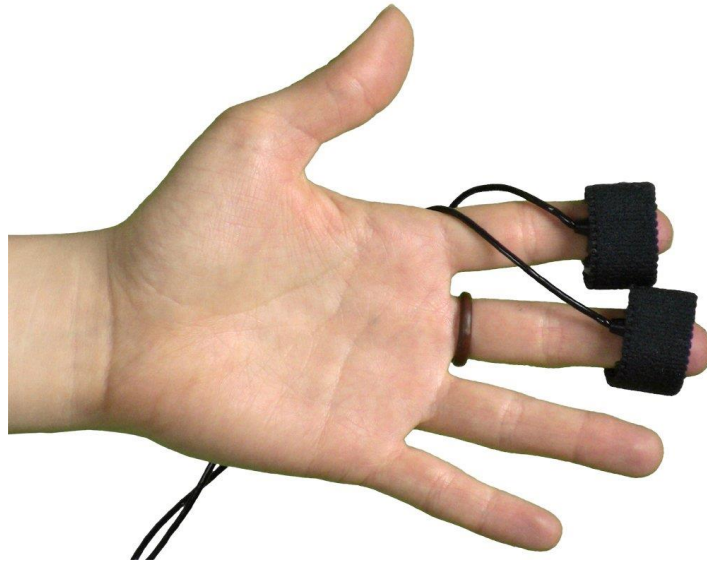


Figure 1. Example of electrodes attached to fingers.



Figure 2. Biopac MP36 system

Prior to the experiment you will be allocated to one of the following control methods:

- 1) Hand control - you will be shown how to open and close your hand during the experiment.
- 2) EMG control with prosthesis - Using software designed for use with myoelectric prostheses, the optimal location for two electrodes will be found. Finding their ideal location involves moving an electrode across your skin and asking you to contract your forearm muscles; the muscles we will target are your wrist flexors and extensors. A prosthetic hand will be placed separately on a table and connected to your arm via electrodes that will be bandaged to your arm) in the location previously identified, the electrodes will detect signals from your forearm muscles flexing.



Figure 3. *Myoelectric prosthetic hand.*

You will then wear a head-mounted display (HMD) *Oculus Rift* (Figure 4) to experience Immersive Virtual Reality (IVR) and have a period of time to familiarise yourself with the environment. You will have a practice session with a separate virtual prosthesis to familiarise yourself with moving the hand via either: 1) opening and closing your hand/2) the prosthetic hand by flexing your arm muscles. This will involve either: 1) resting your right arm on a physical table, 2) resting your right arm on your legs under the table, and then seeing a virtual prosthesis resting on a virtual table.



Figure 4. Oculus Rift HMD.

Your hand/The prosthetic hand will be motion tracked using *Leap Motion* (Figure 5) and will be placed in a specific location so the virtual prosthesis appears in front of you in a specific location on the virtual table.



Figure 5. Leap Motion device and example basic virtual hands.

Once the experiment begins you will be instructed to open and close your hand/flex your arm muscles a number of times while looking at a virtual prosthesis, and being aware of any feelings you have towards the virtual hand. At some point during this a virtual threat will be applied to the virtual hand but there will be no physical harm. During the experiment you will be filmed on video camera to capture your behaviour. Specifically, this will capture your arm and the PC monitor showing the virtual arm to observe any arm movements. As this will be filmed from behind and to the side your face will not be filmed to ensure your confidentiality is maintained. At the end of the experiment, you will remove the HMD and complete a short questionnaire. Following a short break, you will repeat the experiment with the other control method. Once complete, you will be debriefed and asked to fill in a short questionnaire to measure your general feelings in the VR environment.

### **Expenses and payments?**

The research will be entirely voluntary so you will not be paid for your participation in the study.

### **What are the possible disadvantages and risks of taking part?**

There is a possibility that you may feel slightly uncomfortable controlling the prosthetic hand as it involves flexing arm muscles, however this will be checked with you before the experiment commences to ensure you are happy with it.



Also, there is a chance that the HMD may make you feel slightly uncomfortable. This is not expected as motion in the VR environment will be limited and under your own control, however, some people experience motion sickness in VR. You will have a period of time before the experiment commences to check that you feel comfortable in the VR environment and HMD. If you do feel uncomfortable and wish to temporarily stop the experiment and check if you are happy to continue, that will be possible. Any negative feeling during the VR environment is not expected to continue after you leave the experiment. Also, if you wish to withdraw from the study, you can do so at any time without giving reason. If you wish to withdraw your data after the study is complete, you can email the researcher and request your data is removed which can be done up to 31/01/18.

### **What are the possible benefits of taking part?**

We cannot guarantee that you will benefit from taking part in this study, but it is hoped that the knowledge generated will ultimately help to improve the design of electrically powered (myoelectric) prostheses and inform psychological processes involved in prosthesis users accepting their prosthesis as part of them, which could benefit prosthetic rehabilitation.

### **What if there is a problem?**

If there is any problem you can raise this with the researcher (contact details at the bottom) or if this is not suitable then contact his main supervisor –

Dr. Adam Galpin. Email: A.J.Galpin@salford.ac.uk. Telephone: 0161 295 7146. Senior Lecturer, School of Health Sciences, L812b Allerton Building, University of Salford, Salford, Manchester, M6 6PU.

Or -

Prof Susan McAndrew, Chair of Ethics Panel, Email: s.mcandrew@salford.ac.uk.  
Telephone: 0161 295 2778, Room 1.39 Mary Seacole Building, University of Salford, M5 4WT.

### **Will my taking part in the study be kept confidential?**

Your identity will be kept confidential by email correspondence conducted via a University password-protected email account and any data transferred to documents will be anonymised.

Also, you will receive a unique research code which you can provide to me if you wish to remove yourself from the study and then your data linked to this code will be deleted. If one of my supervisors needs to check my analysis of your data, they may have access to it but it will be from the anonymised files not my original emails with you (which could naturally contain your name).

**What will happen if I don't carry on with the study?**

If you decide not to carry on with the study you can provide your research code and then your data will be deleted without the need to provide a reason for this. This can be done up until 01/04/18.

**What will happen to the results of the research study?**

The results will be disseminated through my PhD thesis which this study forms part of, along with publications and/or presentations in academic journal articles and conferences. These outputs will be anonymous so that your identity will remain confidential.

**Who is organising or sponsoring the research?**

The research is being organised by the Centre for Health Sciences Research, University of Salford, Salford M6 6PU. The research is being conducted as part of a PhD project funded by the University of Salford.

**Further information and contact details:**

If you would like to participate in the study or enquire about any additional information please contact Andrew Hodrien at [a.d.hodrien@edu.salford.ac.uk](mailto:a.d.hodrien@edu.salford.ac.uk)

Supervised by Dr. Adam Galpin. Email: [A.J.Galpin@salford.ac.uk](mailto:A.J.Galpin@salford.ac.uk). Telephone: 0161 295 7146. Senior Lecturer, School of Health Sciences, L812b Allerton Building, University of Salford, Salford, Manchester, M6 6PU.

Thank you for taking the time to read about this study and for considering participation.

## Q.2 Consent form

### CONSENT FORM

**Title of study:** Exploring the impact of control method on experience of a prosthesis within Immersive Virtual Reality

**Name of Researcher:** Andrew Hodrien

Please complete and sign this form **after** you have read and understood the study information sheet. Read the statements below and delete yes or no, as applicable in the box on the right hand side.

1. I confirm that I have read and understand the study information sheet version 1, dated 24/10/2017, for the above study. I have had opportunity to consider the information and ask questions which have been answered satisfactorily.
  
2. I understand that my participation is voluntary and that I am free to withdraw at any time, without giving any reason, and without my rights being affected.
  
3. I understand that I can withdraw until 31/01/18 and that any information given until then will be included in the analysis (but not published anywhere) and all data will be removed if I decide to withdraw.
  
4. I agree to wear a head-mounted display, listen to white noise on earphones, wear electrodes on my arm for a motor command and fingers for physiological response, and be filmed during the experiment.
  
5. I understand that my personal details will be kept confidential and not revealed to people outside the research team.
  
6. I understand that my anonymised data will be used in the researcher's Thesis, other academic publications, and conferences presentations.

7. I agree to take part in the study.

Yes/No
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\_\_\_\_\_  
\_\_\_\_\_

\_\_\_\_\_

**Name of participant  
initials or  
signature)**

**Date**

**Signature (type  
add electronic**

\_\_\_\_\_  
\_\_\_\_\_

\_\_\_\_\_

**Name of person taking consent**

**Date**

**Signature**

### Q.3 Debrief sheet



#### Debrief Sheet

**Title of study:** Exploring the impact of control method on experience of a prosthesis within Immersive Virtual Reality

**Name of Researcher:** Andrew Hodrien

Thank you for taking the time to participate in our research and be involved in experiments.

The aim of this study has been to simulate control of a myoelectric (electrically-powered) prosthesis which could influence whether a user feels the prosthesis to be part of them or not (known as 'prosthesis embodiment'). The experiment you participated in was exploring the impact of controlling virtual hand movements via EMG electrodes measuring muscle flexes. This was achieved by you controlling the virtual hand with your own hand for comparison. The impact of this is being explored on the feeling of ownership and agency of a virtual prosthesis. We are also exploring the overall level of embodiment experienced with using the prosthetic hand.

The findings of this study will be used to inform a later study, help guide development of myoelectric prostheses, further understanding of prosthesis embodiment, and potentially benefit prosthesis rehabilitation.

If you wish to withdraw your data from the study can you please contact the researcher and provide him with your unique participant research code which he gave you and then he will remove your data. This can be done up until 31/01/18.

Your emails and contact details will be deleted once the research phase has been completed 01/02/18.

Many thanks again for your time participating in our research.

For any further information or to request withdrawal from the study contact –

Andrew Hodrien: [a.d.hodrien@edu.salford.ac.uk](mailto:a.d.hodrien@edu.salford.ac.uk)

Supervised by Dr. Adam Galpin. Email: [A.J.Galpin@salford.ac.uk](mailto:A.J.Galpin@salford.ac.uk). Telephone: 0161 295 7146. Senior Lecturer, School of Health Sciences, L812b Allerton Building, University of Salford, Salford, Manchester, M6 6PU.

## Appendix R: Participant background information

### Participant background information

Participant number \_\_\_\_\_

Please circle or complete the following information:

Gender: Male Female

Age: \_\_\_\_\_

Hand dominance: Left-handed Right-handed

Experience with Virtual Reality: None Some Familiar

Experience with controlling a myoelectric prosthesis: None Some Familiar

## Appendix S: Prosthesis and hand questionnaire for VR study

### S.1 Experience of virtual prosthesis questionnaire (prosthesis condition)

Participant number \_\_\_\_\_

Please circle a number to represent your level of agreement or disagreement (as shown below) with each statement about your experience. Please be sincere in your responses as there are no right or wrong answers.

1=Strongly Disagree

2=Moderately Disagree

3=Slightly Disagree

4=Uncertain

5=Slightly Agree

6=Moderately Agree

7=Strongly Agree

During the period of time when I was opening and closing the virtual hand...

1. I felt as if I was looking at my own hand

1   2   3   4   5   6   7

2. I felt as if the virtual hand was part of my body

1   2   3   4   5   6   7

3. It seemed as if I were sensing the flexing of my arm muscle in the location where the virtual hand moved

1   2   3   4   5   6   7

4. I felt as if the virtual hand was my hand

1   2   3   4   5   6   7

5. I felt as if my real hand were turning virtual



1 2 3 4 5 6 7

6. It seems as if I had more than one right hand

1 2 3 4 5 6 7

7. It felt as if I had no longer a right hand, as if my right hand had disappeared

1 2 3 4 5 6 7

8. The virtual hand moved just like I wanted it to, as if it was obeying my will

1 2 3 4 5 6 7

9. I felt as if I was controlling the movements of the virtual hand

1 2 3 4 5 6 7

10. I felt as if I was causing the movement I saw

1 2 3 4 5 6 7

11. Whenever I flexed my arm muscle I expected the virtual hand to move in the appropriate way

1 2 3 4 5 6 7

12. I felt as if the virtual hand was controlling my will

1 2 3 4 5 6 7

13. I felt as if the virtual hand was controlling my movements

1 2 3 4 5 6 7

14. It seemed as if the virtual hand had a will of its own

1 2 3 4 5 6 7

Please can you freely describe how you felt towards the virtual prosthesis during the hand movements:

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Have you previously participated in an experiment where you experienced a non-body part (e.g. virtual hand or rubber hand)? If so, can you please describe what was involved:

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## S.2 Experience of virtual prosthesis questionnaire (hand condition)

Participant number \_\_\_\_\_

Please circle a number to represent your level of agreement or disagreement (as shown below) with each statement about your experience. Please be sincere in your responses as there are no right or wrong answers.

1=Strongly Disagree

2=Moderately Disagree

3=Slightly Disagree

4=Uncertain

5=Slightly Agree

6=Moderately Agree

7=Strongly Agree

During the period of time when I was opening and closing the virtual hand...

1. I felt as if I was looking at my own hand

1 2 3 4 5 6 7

2. I felt as if the virtual hand was part of my body

1 2 3 4 5 6 7

3. It seemed as if I were sensing the movement of my hand in the location where the virtual hand moved

1 2 3 4 5 6 7

4. I felt as if the virtual hand was my hand

1 2 3 4 5 6 7

5. I felt as if my real hand were turning virtual

1 2 3 4 5 6 7

6. It seems as if I had more than one right hand

1 2 3 4 5 6 7

7. It felt as if I had no longer a right hand, as if my right hand had disappeared

1 2 3 4 5 6 7

8. The virtual hand moved just like I wanted it to, as if it was obeying my will

1 2 3 4 5 6 7

9. I felt as if I was controlling the movements of the virtual hand

1 2 3 4 5 6 7

10. I felt as if I was causing the movement I saw

1 2 3 4 5 6 7

11. Whenever I moved my hand I expected the virtual hand to move in the appropriate way

1 2 3 4 5 6 7

12. I felt as if the virtual hand was controlling my will

1 2 3 4 5 6 7

13. I felt as if the virtual hand was controlling my movements

1 2 3 4 5 6 7

14. It seemed as if the virtual hand had a will of its own

1 2 3 4 5 6 7

Please can you freely describe how you felt towards the virtual prosthesis during the hand movements:

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Have you previously participated in an experiment where you experienced a non-body part (e.g. virtual hand or rubber hand)? If so, can you please describe what was involved:

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## Appendix T: Summary of embodiment studies

### Summary of embodiment studies

**Rationale:** In order to understand whether the optimal latency of the demo being developed for the VR study is acceptable for inducing embodiment, an in-depth review of psychological embodiment studies is necessary, particularly focusing on visuomotor stimulation studies (those where body ownership is induced in the style of a RHI/VHI using active movement as the stimulation, i.e., movement initiated by the participant rather than passive movement controlled by the experimenter or via tactile stimulation – these are later referred to as active movement) as involves both ownership and agency and is comparable to the planned method of stimulation. This aims to identify how embodiment is specifically affected by delays introduced in stimulation (later referred to as an asynchronous group).

**Method of selection:** A snowball sampling approach was adopted starting from a recent review paper of body ownership techniques (Kilteni, Maselli, Kording, & Slater, 2015) along with previously identified studies which used active movement to induce embodiment. All relevant papers mentioned in the review paper were checked for inclusion and then any further paper mentioned which was not included in the review paper were checked. Additionally, papers published since the review paper were checked by checking papers “as cited by” in google scholar.

**Inclusion criteria:** Experimental studies inducing embodiment (ownership or agency) using active movements. Papers need to include a delay condition and report details of this.

**Results:** 40 papers were reviewed out of which 14 for active movement were found to be suitable for inclusion.

See Table T1 for a summary of details from relevant active movement papers identified from the review. This includes paper authors, the delay condition amount (which includes any intrinsic delay of the protocol reported by the paper), the stimulation amount in seconds (i.e., how long the stimulation lasted for to induce embodiment) and number of movements (if reported), whether a significant difference for ownership was found between the synchronous (no delay) and asynchronous (delay) conditions, the same for agency, and also (where

relevant) if there was a significant difference between experimental questions (measuring embodiment) and control questions (not measuring embodiment) in the synchronous condition (this is an additional measure of embodiment which some papers look at). All measures of ownership and agency are from an embodiment questionnaire.

Table T1

*Summary of details of 14 relevant papers identified from review of active movement studies*

<b>Paper</b>	<b>Delay (ms)</b>	<b>Stimulation (sec) (amount)</b>	<b>Ownership (sig diff / no sig diff)</b>	<b>Agency (sig diff / no sig diff)</b>	<b>Ownership (exp vs control questions)</b>	<b>Agency (exp vs control questions)</b>
Tsakiris, Longo, and Haggard (2010)	600	36 (72)	Sig diff	Sig diff		
Kalckert and Ehrsson (2012)	500	180 (180)	Sig diff	Sig diff	Sig diff	Sig diff
Kalckert and Ehrsson (2014a)	500	90 (90)	Sig diff	Sig diff	Sig diff	Sig diff
Kalckert and Ehrsson (2014b)	500	90 (90)	Sig diff	Sig diff	Sig diff	Sig diff
Riemer, Fuchs, Bublitzky, Kleinbohl, Hooltz, and Trojan (2014)	570- 2070	90 (18-30)	Sig diff	Sig diff	N/A	N/A
Riemer, Kleinböhl, Hölzl, and Trojan (2013)	570- 2070	180	Sig diff	N/A	N/A	N/A
Ma and Hommel (2013)	2000	60	Sig diff	N/A	N/A	N/A
Ma and Hommel (2015a).	5010	90	Sig diff	N/A	N/A	N/A
Zhang and Hommel (2016)	350- 500	180	No sig diff	Sig diff	N/A	N/A
Ma, Lippelt, and Hommel (2017)	3000	120-180	Sig diff	Sig diff	N/A	N/A
Kalckert and Ehrsson (2017)	500	120 (120)	Sig diff	N/A	N/A	N/A
Jenkinson and Preston (2015)	500	60 (60)	Sig diff	N/A	Sig diff	No sig diff
Ma and Hommel (2015b)	2000	60	Sig diff	Sig diff	N/A	N/A
Caspar, De Beir, Da, Yernaux, Cleeremans, and Vanderborght (2015)	500	180 (180)	Sig diff	Sig diff	N/A	N/A

*Note:* Exp = experimental questions measuring embodiment

Referring to the table above significant and non-significant differences found between the synchronous and asynchronous conditions were plotted on graphs to identify what level of delay starts to disrupt embodiment (i.e., a significant difference for 500ms on the graph shows embodiment is significantly less when 500ms delay is introduced). See Figure T1



showing the papers which found a significant ownership score difference between the synchronous condition and asynchronous condition (lower sig difference refers to the delay amount used or the lower value if a range of values were used, upper refers to the upper value for delay, where relevant). Also shown is one paper which found a non-significant difference which highlights there was no difference in embodiment between 0ms and 350-500ms (Zhang and Hommel, 2016).

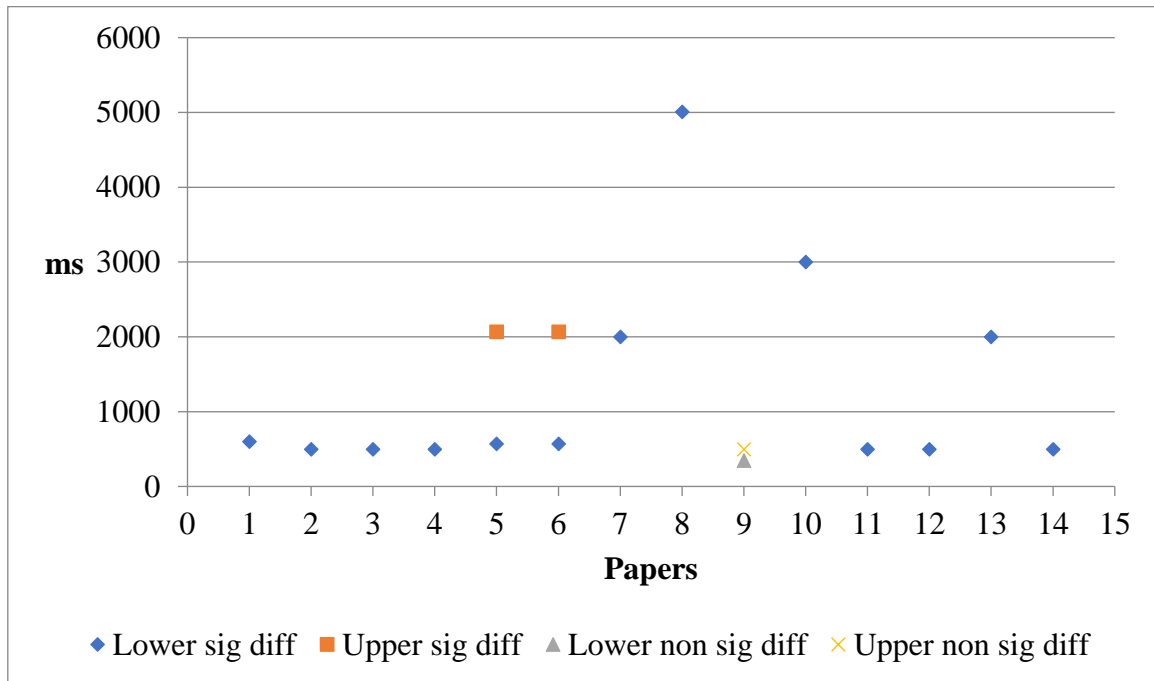


Figure T1. Ownership score differences between synchronous and asynchronous conditions.

Similar to above, see Figure T2 showing the equivalent differences for agency scores.

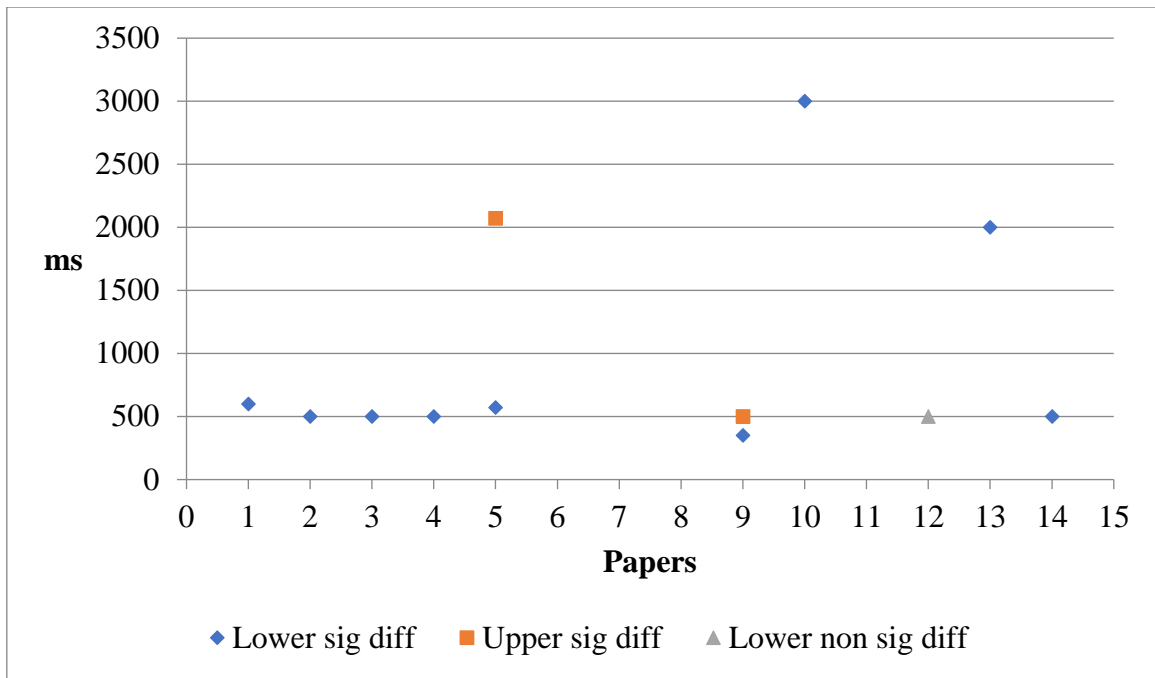


Figure T2. Agency score differences between synchronous and asynchronous conditions.

See Figure T3 for the various stimulation times used in studies.

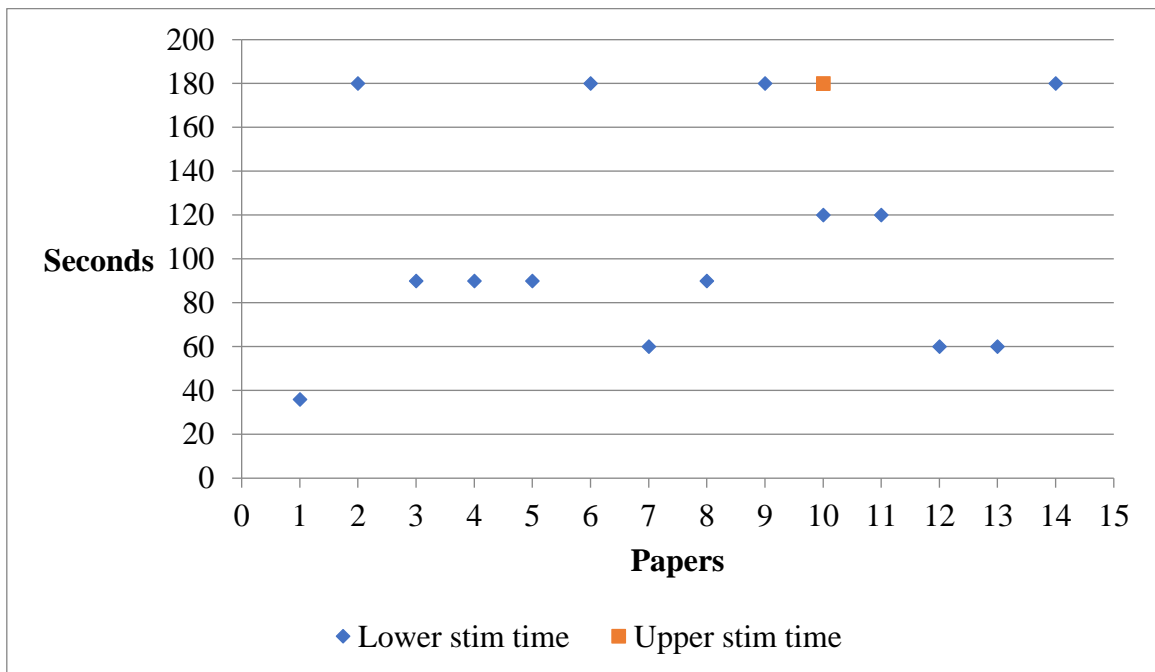


Figure T3. Stimulation time in seconds used in studies.

See Figure T4 for the various stimulation amounts (number of hand movements) used in studies.

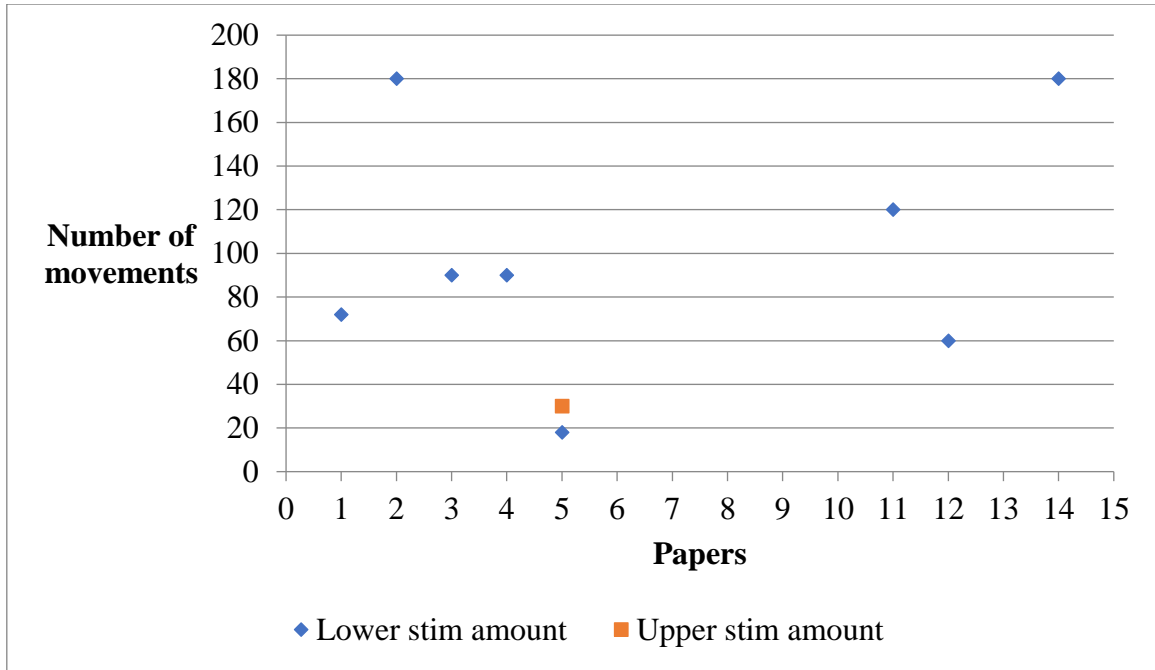


Figure T4. Stimulation amount in number of hand movements.

See Figure T5 for the various stimulation rates (number of hand movements per second) used in studies.

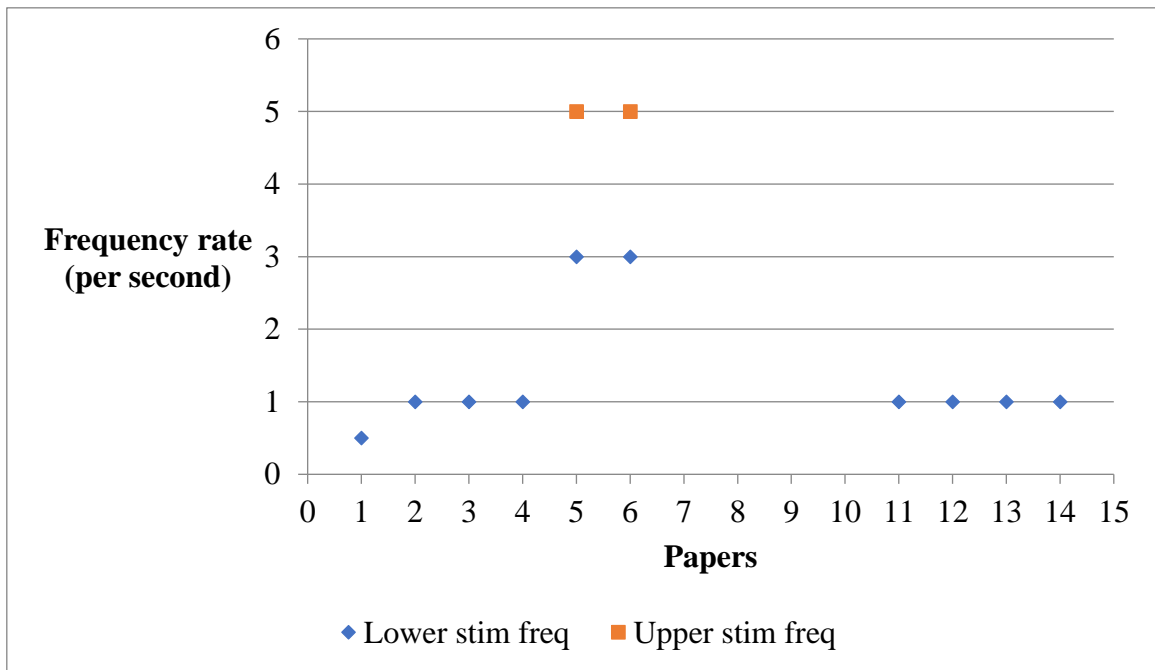


Figure T5. Stimulation rate in frequency per second.

As highlighted in the graphs above the active movement studies it is unclear exactly where embodiment (for either ownership or agency) starts to occur. Similar to above, visuotactile

stimulation (embodiment induced via tactile stimulation) studies tend to include a 500ms delay. However, 3 specific papers which measured a range of delays or delays smaller than 500ms are reviewed in Table T2 below (1 of these was not suitable for inclusion).

Table T2

*Summary of details of 2 relevant tactile papers identified from review of studies*

	Embodiment method	Embodiment measurement	Delay condition <i>ms</i>	Stimulation sec (amount)	Ownership (sig diff / no sig diff)
Shimada, Fukuda, and Hiraki (2009)	RHI	questionnaire (individual ownership questions, individual control questions).	185/285/385/485/585	180 (180-360)	Sig diff (all delay conditions)
Shimada, Suzuki, Yoda, and Hayashi (2014)	RHI	questionnaire (individual ownership questions, individual control questions)	185/285/385/485/585	60-180 (60-180)	Sig diff (all delay conditions)

In Shimada et al. (2009) further analysis on one experimental question found a significant ownership effect (criteria of score being significantly higher than 0) in the synchronous (85 intrinsic delay) and 185/285/385/485 asynchronous conditions. They also found a significant difference for this ownership score between the 85-285ms and 585ms conditions.

In Shimada et al. (2014) further analysis of ownership questions found these were significantly higher in 85ms than 485ms, and significantly higher in 185ms than 585ms conditions.

The above studies suggest variable delays of 200-300ms have been found to begin reducing the sense of embodiment (e.g., Shimada, Fukuda, & Hirak, 2009; Shimada, Suzuki, Yoda, & Hayashi, 2014). However, whilst Shimada et al. (2009) highlight that delay of less than 300ms is preferable to achieve a strong RHI effect; they found there can still a weaker RHI with 400-500ms delay. Thus, a total delay (prosthesis hand and hand tracking) should aim to be below 300ms.

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## Appendix U: Prosthetic hand delay

Taken from Chadwell, A. E. A. (2018). *The Reality of Myoelectric Prostheses: How do EMG skill, unpredictability of prosthesis response, and delays impact on user functionality and everyday prosthesis use?* (Doctoral dissertation, University of Salford). Figure 71 taken from Appendix 4 delays, sub-section A4.7.2. Results.

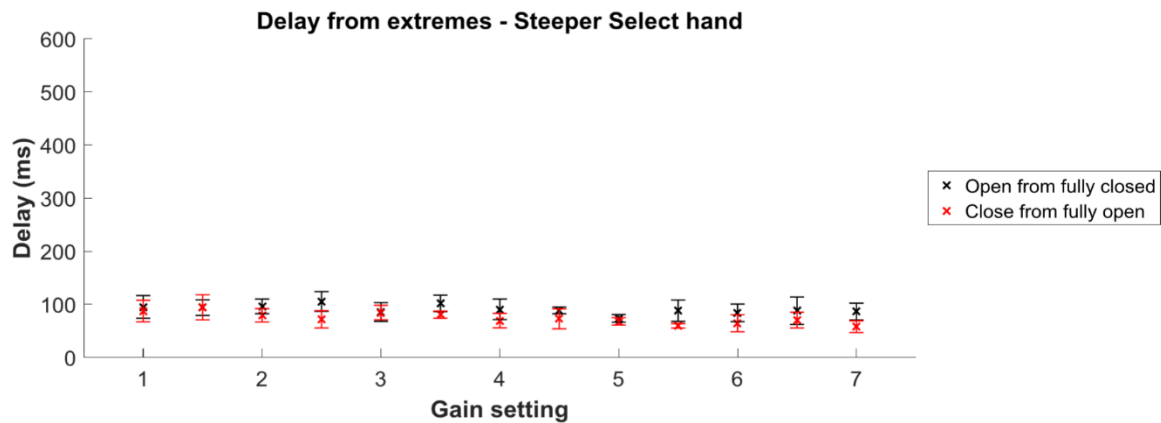


Figure 71. “Delay” recorded at each gain setting for a threshold controlled Steeper Select hand. “Delays” were measured from the extremes of hand open or closed.

Figure 78 taken from Appendix 4 delays, sub section A4.8.3. Delay to close measured from neutral aperture vs fully open.

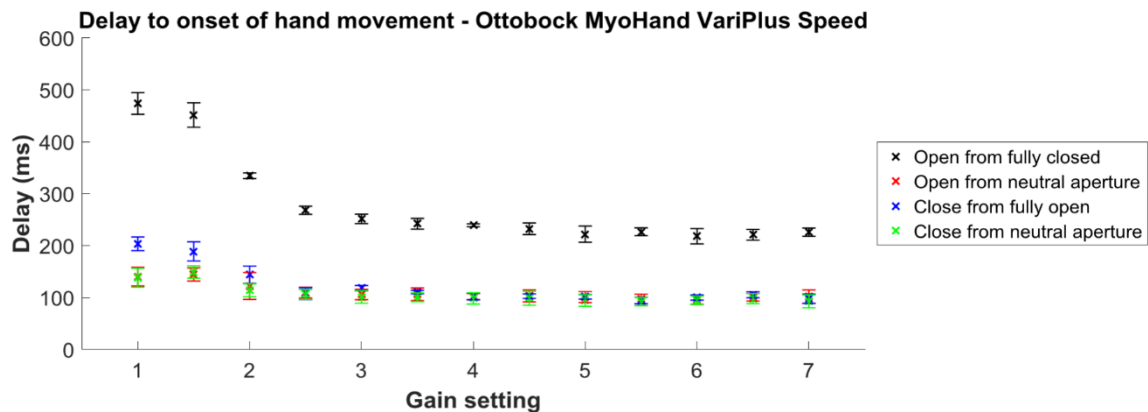


Figure 78. “Delay” recorded at each gain setting for a proportionally controlled Ottobock MyoHand VariPlus Speed. “Delays” were measured from the extremes of hand open or closed. Both opening and closing were also measured from a range of neutral starting hand apertures.

## Appendix V: Leap motion latency and accuracy

### An investigation into Leap Motion latency and accuracy

#### Introduction.

For the VR experiments the demo being used involves hand motion tracking using Leap Motion. This was developed by Leap Motion (<https://www.leapmotion.com>) for the purpose of gesture interaction and so has the useful application of hand gesture recognitions, along with the practical benefit of only needing the controller removing the need for a hand tracking glove to be used (Shao). Two potential concerns have been identified with using Leap Motion, one being the intrinsic delay (referred to here as latency and the other being the device's accuracy in motion tracking of a prosthetic hand). An investigation into these two factors follows below to help identify the overall latency and accuracy the system will provide during experiments along with deciding the best conditions to improve these factors. This is important so that the conditions are conducive to encourage embodiment through minimising latency and maximising accuracy.

***Psychological impact of delay on embodiment.*** Aside from the aim of minimising delays as much as possible it is important to consider the psychological implication of this for the experiments exploring embodiment. As one of the conditions is aimed to encourage embodiment of a virtual prosthesis the threshold of synchrony or asynchrony between sensory inputs should be identified from prior embodiment studies. The temporal contiguity of signals has been highlighted as being vital for self-body recognition which can include both ownership and agency (e.g., Botvinick & Cohen, 1998; Franck et al., 2001; Leube et al., 2003; Shimada et al., 2009; Shimada, Hiraki, & Oda, 2005). Studies using *rubber-hand illusion* (RHI, Botvinick & Cohen, 1998) techniques to explore embodiment often have a delay of 500ms in the asynchronous condition. This temporal discrepancy is considered to significantly reduce the RHI effects (Shimada et al, 2009).

Studies which have explored this further have found variable delays of 200-300ms to begin reducing the sense of embodiment (e.g., Shimada et al., 2009; Shimada, Qi, & Hiraki, 2010; Shimada et al., 2014). However, whilst Shimada et al. (2009) highlight that delay of less than 300ms is preferable to achieve a strong RHI effect; they found there can still a weaker RHI with 400-500ms delay. Thus, a total delay (prosthesis hand and hand tracking) should aim to be below 300ms and ideally 200ms.

### **Leap Motion latency background.**

Whilst the latency of Leap Motion is lower than other similar products the exact latency depends on a variety of factors (<http://blog.leapmotion.com/understanding-latency-part-1/>). The official Leap Motion Blog has detailed such factors which can introduce a delay between a movement and when the visual representation of this movement is displayed. Two pages on this blog devoted to latency were reviewed along with a *Leap Motion VR Best Practices* document.

**Summary.** In summary, the Leap Motion blog mentions that a number of factors influencing latency are outside of the device and advises the following actions to improve the experience:

- 1) Connect the device via a USB3 port – to increase transfer processing rates.
- 2) Use a 120hz monitor – to provide a low response time.
- 3) Disable vertical synchronization (VSync) in the graphics settings.
- 4) Select “high speed” mode – to improve speed and frame rate in exchange for lower tracking quality.
- 5) Use a CRT display – no input lag and high refresh rates.

### **Testing latency**

**Testing stage 1.** Initial latency testing involved using a desktop application demo of just a basic virtual hand (*capsule hand*) with no environment using *Unity 5.4.2* software. The Leap Motion Controller (using *Leap Motion Orion* software) was placed on the desk facing upwards and I moved my left hand in an arc right and left over the device while the virtual hand was displayed on the PC monitor behind it. This was filmed with a Sony Xperia Z5 compact camera which films at 30 frames per second (fps). The video was camera then checked frame by frame in Windows Movie Maker software. Using a 30fps camera if there is no noticeable delay between my hand and the virtual hand moving, this means any delay must be below 30 milliseconds (ms) as there is 0.03 frames per ms or 1 frame per 30ms. In viewing the video, the virtual hand appeared to move roughly in sync with my hand, but when checking frame by frame there was a 1 or 2-frame difference between the virtual hand moving or stopping moving, compared to my hand. This suggests a 30-60ms delay. It was decided that a higher frame rate camera should be used and instead of hand movements the

delay should be tested in a similar way to how the actual experiments will appear (i.e., in my virtual environment with the virtual hand opening and closing).

**Testing stage 2.** A virtual environment created in Unity involved looking down at a desk while seeing a virtual hand and arm. The Leap Motion Controller was attached to the front of an *Oculus Rift* head-mounted display (HMD) - see Figure V1.



Figure V1. Leap Motion attached to Oculus Rift HMD.

This was looking down at my right hand while the virtual hand was displayed on a monitor behind. Two versions of the demo were created each utilising a different mode selected for Leap Motion (as mentioned above). Settings for a high-speed mode and precision mode in Leap Motion were not found but what is believed to be an equivalent setting called *Robust Mode* appears to switch between these modes. When selected this improves tracking reliability but at the possible expense of increased latency.

Further conditions to improve latency were implemented. VSync was switched off on both the PC and the laptop which the demos would be tested on, as suggested by the Leap Blog. On the PC, the Leap Motion Controller was attached via USB3. However, on the laptop it is believed that only USB2 can be used as there is a problem getting Leap Motion to connect via the USB3 on the base station. A Panasonic Lumix DMC-FZ200 camera was used to film in high speed. Originally videos were filmed in the highest setting of 200fps. However once videos were uploaded to the analysis software and checked frame by frame it became

apparent that the reduced quality of the videos (with this setting) made analysis difficult. It was decided to re-film all videos in 100fps which could film in HD so the following analysis is based on those videos.

**Testing with laptop.** An MSI GS30 2M Shadow laptop with base station was used to run the Unity demos and these were displayed on a separate standard PC monitor (ProLite B1902S, refresh rate 60Hz) as while the demos can be seen via the Oculus Rift, the laptop is unable to display this on the screen. The laptop includes an Nvidia GeForce GTX 980 graphics card and the CPU is an Intel Core I7.

The Leap Motion setting was set in either precision or high-speed mode (based on the robust mode being switched on and off), and then the relevant demo was run for each. The camera was attached on a tripod and filmed me opening and closing my hand a number of times while also capturing the virtual hand behind this. See Figure V2 for an example of this.



*Figure V2.* Example of laptop filming setup.

**Testing with PC.** Demos were run and filmed the same as with the laptop but using a desktop Viglen genie PC. This includes an iiyama ProLite B2280HS monitor with a refresh rate of 60Hz and a Nvidia GeForce GTX 750 Ti graphics card. The CPU is an Intel Core I7.

**Analysis.** Videos were analysed using Tracker 4.96 (Open Source Physics, <http://www.opensourcephysics.org/items/detail.cfm?ID=7365>). The frames when both my hand and virtual hand started closing were recorded (on separate Excel spreadsheets for each video), and the frames when both stopped closing was also recorded. This was repeated for both hands opening. Three cycles of this were included in the analysis to check consistency and using an average of the three cycles. The following acronyms are used in the analysis to represent the movements:

- *HBC* = hand begins closing (i.e., frame when hand moves)
- *HSC* = hand stops closing (i.e., frame when hand stopped moving so was no different to previous frame)
- *HBO* = hand begins opening
- *HSO* = hand stops opening.
- *VHBC* = virtual hand begins closing
- *VHSC* = virtual hand stops closing
- *VHBO* = virtual hand begins opening
- *VHSO* = virtual hand stops opening.

Presented here is a summary of results taken from the Excel spreadsheets. See Table V1 for overall delay figures for both the laptop and PC in each of the Leap Motion modes. The ms are rounded up or down. These are calculated as an average of the delays for the four hand movements (*HBC*, *HSC*, *HBO*, and *HSO*).

Table V1  
*Average overall delays (ms) summary*

	Laptop	PC
Precision mode	106	120
High-speed mode	82	95

Possibly more relevant to experiments though is the onset delays involving only when the hand begins to close or open (not when the hand has finished its movement). This is because if a prosthetic hand is used and operated with EMG the onset of movement delay will likely to be the most noticeable. For this reason, see Table V2 for just the average onset delay

figures. Also, it is noted that delays in the analysis have appeared quite variable between the different hand movements, so the below figures potentially represent a more accurate delay which would be observable in experiments.

Table V2

*Average onset delays (ms) summary*

	Laptop	PC
Precision mode	133	122
High-speed mode	87	102

### **Leap Motion accuracy background**

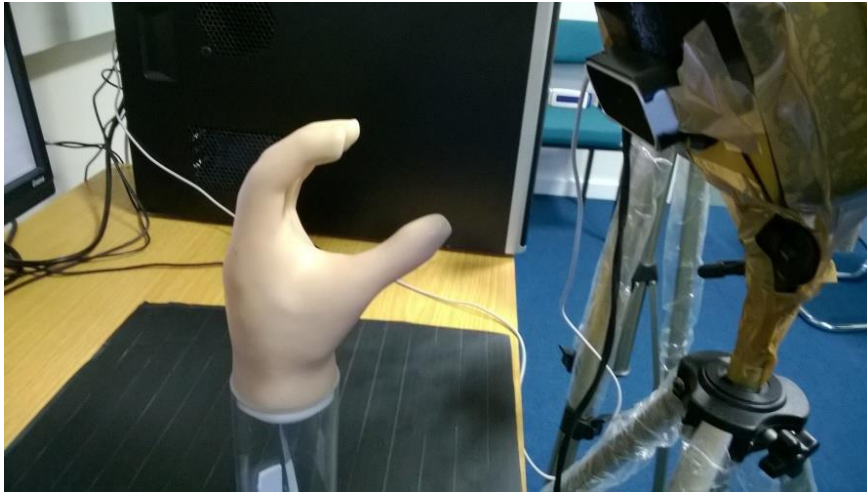
Overall, the Leap Motion Controller can recognise and track hand gestures accurately (Weichert, Bachmann, Rudak, & Fisseler, 2013), however, when fingers are occluded there can be a reduced quality of tracking data sometimes resulting in an incorrect prediction of the intended gesture (Shao). Another potential issue is the hand not being accurately recognised because of the background reflecting light. The Leap Motion Controller uses infrared light to capture a hand in the space so any interference from the background could disrupt the accuracy of the hand being recognised. Hand embodiment studies using both Oculus Rift and Leap Motion have utilised anti-reflective tape on a shelf with the Leap Motion Controller looking down at this to minimise infra-red interferences (Argelaguet et al., 2016; Hoyet, Argelaguet, Nicole, & Lécuyer, 2016).

### **Testing accuracy**

**Testing stage 1.** I purchased some anti-reflective matte black tape and made a base from cardboard covered in tape. This can be easily placed on a table with the hand on top. For accuracy testing, prosthetic hands (left *Steeper* and right *Ottobock* myoelectric hands) have been used instead of actual hands as it is important to know if Leap Motion can recognise these hands moving. Initial observations of the prosthetic hands were made with one or two hands resting on the base and holding the Oculus Rift and Leap Motion over them whilst in different configurations.

**Testing stage 2.** A left *Steeper* myoelectric prosthetic hand was slotted into a clear tube used to display the hand and attempt to keep it in the same location. The tube was either

placed sitting upwards on its end with the hand positioned vertically with the palm and fingers facing the Leap Motion Controller, or with the tube laying down on its side and the hand protruding from the right-hand side. In the laying down condition, the tube and hand were found to move a lot with the hand becoming separated from the tube, so the tube was taped to the base and the hand taped to the tube. See Figure V3 showing the Leap Motion Controller facing the hand with the Oculus Rift attached to a tripod for stability.



*Figure V3.* Example of positioning of Leap Motion Controller in relation to hand.

See Figures V4 and V5 for example photos of the hand in the upright and laying down position, respectively.





*Figure V4.* Example photo of hand in the upright position.



*Figure V5.* Example photo of hand in the laying down position.

**Analysis.** Videos were analysed using Tracker 4.96 (Open Source Physics). The frames when both the prosthetic hand and the virtual hand were closing were analysed to observe the accuracy of tracking. This was repeated for the hand opening and 5 cycles of the

hand closing and opening were analysed representing 10 movements (5 per hand opening and closing). Separate spreadsheets were used for each hand configuration. Overall averages for hand movements were assessed along with separating hand closing and opening movements in case accuracy differs between these. The following acronyms are used in the analysis to represent the movements:

- *HDC* = myoelectric hand during closing (i.e., the period in which the hand is closing),
- *HDO* = myoelectric hand during opening (i.e., the period in which the hand is opening).

Also, the following descriptive labels for behaviour of the virtual hand are:

- *Virtual hand present* = the virtual hand is displayed during the movement (coded as 1 = present for whole time, 0 = not present at least some of the time).
- *Virtual hand opens/closes* = the virtual hand opens or closes as relevant to the movement of the myoelectric hand (coded as 1 = generally displays the appropriate movement, 0 = no movement in the appropriate direction).
- *Virtual fingers vanish* = one or more virtual fingers/thumb vanish during movement (coded as 1/2/3/4/5 = the number of fingers/thumb which vanish, 0 = no fingers/thumb vanish).
- *Number of incorrect virtual fingers* = the number of fingers which display noticeably incorrect movement such as moving the wrong direction (coded as 1/2/3/4/5 = the number of fingers/thumb which move in the wrong direction, 0 = no fingers/thumb move in the wrong direction).
- *Virtual arm in incorrect position* = the arm is displayed in a different angle than perpendicular to the hand (coded as 1 = generally displays the appropriate movement, 0 = no movement in the appropriate direction).

See Table V3 for a summary of accuracy figures in percentages taken from the Excel spreadsheet for hand in the upright position.

Table V3

*Overall percentages and specific percentages for hand during closing and hand during opening whilst in the upright position*

	Virtual hand present	Virtual hand opens/closes	Virtual fingers vanish	Number of incorrect virtual fingers	Virtual arm in incorrect position
Overall %	100	100	0	40	0
HDC %	100	100	0	40	0
HDO %	100	100	0	40	0

See Table V4 for a summary of accuracy figures in percentages taken from the Excel spreadsheet for hand in the laying down position.

Table V4

*Overall percentages and specific percentages for hand during closing and hand during opening whilst in the laying down position*

	Virtual hand present	Virtual hand opens/closes	Virtual fingers vanish	Number of incorrect virtual fingers	Virtual arm in incorrect position
Overall %	100	100	0	8	100
HDC %s	100	100	0	0	100
HDO %	100	100	0	16	100

As shown in tables above, in both positions, the virtual hand was present all of the time, the hand opened or closed as appropriate to the myoelectric hand movement all of the time and none of the fingers vanished. However, the positions differ in regard to fingers moving incorrectly and the arm presented in an incorrect position. Whilst upright, the arm is in the correct position but 2 (40%) fingers moved incorrectly part of the time. This occurred for all hand closing and opening movements. Whereas, whilst laying down, the arm was in an incorrect position all of the time and also 2 (8%) of the fingers moved incorrectly but only out of 2 out of 5 hand opening movements.

## Discussion

**Latency.** Delays measured appear to be higher than expected based on suggestions from Leap Motion regarding the latency their device adds and suggestions that it is possible to achieve below 30ms in particular set-ups. Advice was followed to help maximise this by turning Vsync off, using USB3 (for the PC), changing the device mode, and comparing between a PC and gaming type laptop. The laptop had overall lower latency than the PC, except for in the precision mode, when observing just the average onset delays where latency was higher than the PC (for overall delays the laptop had a lower latency than the PC in precision mode). Also, for both the laptop and PC the high-speed mode had a lower latency than the precision mode. The lowest latency achieved was for the laptop in high-speed mode at 82ms average overall delay or 87ms average onset delay.

Points to consider which might explain the discrepancy between these results and suggestions from Leap Motion include 1) the method of assessing delay may not be accurate, 2) the monitor refresh rate, 3) USB3, and 4) the contribution of latency from other sources than the Leap Motion Controller.

1) The method of observing individual frames to see the difference between the fingers of my hand and virtual hand moving was noticeably difficult at times. The videos needed to be zoomed in on the hands to see when movement started and at times small movements in the hand (not the fingers and thumb moving closer or apart) made this difficult. This is possibly highlighted by the variable amounts of delay found between the types of hand movement. Such factors could mean the delay noted may not accurately reflect the actual latency of Leap Motion. It could be that aspects of the environment or viewing angle of the hand means the finger or thumb movements are only registered once they have clearly moved a certain distance. If so, the delay figures could be inflated, as those observed would include these additional frames, along with the frames representing the delay in processing and presenting the virtual hand movement. Each frame is 10ms so this could have a potentially significant impact. To clarify this, perhaps an alternative method would need to be explored. Alternatively, delays measured using the prosthetic hand might produce different results compared to an actual hand.

2) Leap Motion suggested using a gaming monitor to improve latency and whilst the laptop used does have a more powerful graphics card it needs to be connected to an external

monitor to display what is seen within Oculus Rift HMD. It was found that the monitor used was 60Hz, which in hindsight means the full benefits of using a gaming display may not be utilised here. It is recommended that a separate 120Hz display is sought and connected to the laptop to check if this improves latency or consider testing with a different system if latencies observed are considered too high.

3) The base station connected to the laptop includes a USB3 however I was advised there is a known problem with getting the Leap Motion Controller to be recognised via this as it asks to be connected directly via the laptop, which I believed was USB2. However, upon further searching specifications of the laptop online (<https://www.msi.com/Laptop/GS30-2M-Shadow.html#hero-specification>) it is noted as having USB3 ports. Thus, this particular point may be void.

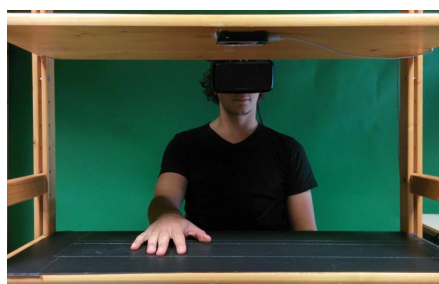
4) Lastly, the amount of latency added by the Leap Motion Controller may be significantly smaller than that observed in testing. According to Leap Motion, in a particular set-up their device only contributes just over 10% of the latency. The contribution of other potential sources of delay should be further investigated if the latencies observed are considered too high.

Aside from potential issues causing a higher latency observed in the current testing, two other aspects need to be considered to decide whether these figures are suitable or not these include the additional delay potential added by the prosthetic hand and the psychological impact of delays on embodiment.

***Prosthesis delay.*** An additional delay will be introduced by an inherent electromechanical delay when opening and closing a myoelectric hand. Based on an investigation into delays by PhD student Alix Chadwell, the delay can vary between the Steeper hand and Ottobock hand, whether the hand is opening or closing, and whether it is opening or closing fully or from a neutral position. The Steeper hand produced a fairly consistent amount of delay in both a full opening and closing of below 100ms. The Ottobock hand could achieve around 100ms delay if the hand was opening and closing from a neutral position. These figures also match those found to match an optimal controller delay for myoelectric prostheses (Farrell & Weir, 2007).

**Accuracy.** Whilst noting further accuracy analysis should be conducted, to both further improve the environment and fine-tune the best position for the prosthetic hand (if used) to be in to avoid motion tracking errors, it appears that it is possible to capture prosthetic hand movements using Leap Motion. Unfortunately, at the time of filming for accuracy testing the Ottobock hand was not working, so was unavailable to be included in the analysis to compare with the Steeper hand (although it was casually observed beforehand while trialling different positions). This could perhaps be later assessed to decide if one hand is significantly better for motion tracking. On first impression the Ottobock hand seemed more at risk of tracking errors in certain positions. Ultimately a trade-off may have to be made between certain decisions based on the most accurate hand and position within any practical constraints of the experiments.

As mentioned earlier hand embodiment studies using both Oculus Rift and Leap Motion have utilised anti-reflective tape on a shelf with the Leap Motion Controller looking down at this to minimise infra-red interferences (Argelaguet et al., 2016; Hoyet et al., 2016). Whilst similar tape was used in the current testing this and other environmental aspects could be considered further to help maximise tracking. Also, if the Leap Motion is considered to be particularly risky in tracking a prosthetic hand while attached to the Oculus Rift HMD (e.g., because participants could freely move their head whilst looking down at the hand which could introduce interferences) then an alternative situation could be considered. One example is in the studies mentioned above where the Leap Motion Controller was in a fixed position (attached to a shelf) above looking down at a moving hand (see Figure V6).



*Figure V6.* Example of experimental setup with Leap Motion fixed to shelf.

## Conclusion

In conclusion, latency and accuracy testing has revealed that with some fine-tuning and potential further testing the Leap Motion Controller could be used in experiments to track prosthesis movements. Taking into account prosthesis delays and findings from embodiment research the latencies currently found could be acceptable for the purpose of exploring embodiment. However, as noted, latencies are higher than expected (based on suggestions from Leap Motion) so further exploration of this could be conducted if there is a concern about the amount of delays measured.

## New latency testing

After the demo was developed further for use on the laptop additional latency analysis was conducted. For updated testing just onset of movement was focused on but number of movements per video was raised to 10 – 5 hand closing and 5 hand opening movements. The following acronyms are used in the analysis to represent the movements:

- *HBC* = hand begins closing (i.e., frame when hand moves)
- *VHBC* = virtual hand begins closing
- *HBO* = hand begins opening
- *VHBO* = virtual hand begins opening

Presented here is a summary of results taken from the Excel spreadsheets. See Table V5 for average repeated trials delays (in ms) using my hand and comparing between latency and accuracy Leap Motion modes. These are calculated as an average of 10 movements.

Table V5

*Average repeated trial delays (my hand) (ms)*

	My hand latency	My hand accuracy
	99	109
	90	102
	95	106
Average	95	106

See Table V6 for average repeated trials delays using the Ottobock prosthetic hand.

Table V6

*Average repeated trial delays (Ottobock hand) (ms)*

	Ottobock latency	Ottobock accuracy
	104	107
	103	103
	105	108
Average	104	106

See Table V7 for an overall summary of delays across conditions.

Table V7

*Average overall delays (ms) summary*

	Latency	Accuracy
My hand	95	106
Bock hand	104	106

### **New accuracy testing**

For the updated accuracy analysis, a number of changes were considered since the earlier analysis as at the time this wasn't explored in as much depth. Changes were made based on greater consideration of earlier findings, how inaccuracy in tracking could influence an experience for the participant, and ongoing use of the tracking system and prosthetics to identify how closely the virtual hand matches the prosthetic hand movements. The Leap Motion system makes a hypothesis of hand and finger positions so if it struggles identifying the prosthetic hand position then it may display the virtual hand in a generally "correct" position (e.g., open, closed, or moving in the appropriate direction), but the exact positioning of the fingers/thumb may not match the exact position of the prosthetic fingers/thumb. With the way the prosthetic hands open and close this issue is quite prevalent in motion tracking of the hand.



It appears the system thinks the hand is opening unnaturally so when the hand is fully opened the virtual thumb remains in a more “natural” position with the hand open but the thumb being closer to the fingers. As a result of this, when the prosthetic hand closes the thumb moves in the correct direction but ends up over the fingers, whereas the prosthetic thumb ends up touching the tips of the fingers.

Taking the above and other observations into consideration, it was decided to base accuracy judgements not on the exact positioning of virtual fingers relative to prosthetic fingers but rather on how virtual fingers behave relative to the overall movement (e.g., fluid movement when opening or no movement when the hand is still) along with other more broad categories of accuracy based on the hand. This somewhat less “strict” approach to accuracy analysis is considered to be acceptable for the experiments for 2 reasons: 1) Participants will be controlling movements with muscle flexes with the knowledge that a particular muscle should lead to the virtual hand opening or closing (and no muscle flexes should lead to the hand remaining still). This means the exact position of the virtual fingers relative to the prosthetic fingers is less important rather than the general movement and positioning of the hand. 2) Participants will be wearing a HMD whilst controlling the hand so they won’t be able to compare the prosthetic hand movements with virtual hand movements.

A previous category of the virtual fingers vanishing was removed as this was found to be redundant with individual fingers not vanishing, but rather the complete hand vanishing. Virtual arm in incorrect position was removed as previous testing just used the hand in a clear tube and it was later found that when the hand opened or closed the virtual arm would sometimes be in an incorrect position relative to the virtual hand. This issue has since been improved by placing a black cover (currently cleaning cloth for glasses) over the tube which improves the accuracy of the virtual arm. A further change made is to make all the categories titles and descriptions represent a “positive” indication of accuracy. Previously, some categories were framed as accuracy (e.g., *Virtual hand present*) whereas others were focusing on inaccuracy (e.g., *Number of incorrect virtual fingers*). Having all categories focus on accuracy makes for a clearer observation of the data and easier calculation of a total accuracy “score” combining all categories.

Also taken into consideration is factors identified in embodiment literature which could impact on experience of the virtual prosthesis. One aspect which disrupts embodiment

is if the hand observed is the wrong hand compared to the one being stimulated or causing the stimulation. For this reason, a category was included noting if the virtual hand remains as a right hand the whole time. An additional factor influencing embodiment is the congruence of the general position of the hand being observed with the hand being stimulated. Whilst a participant's own hand is not being stimulated (thus may not be as significant an issue) they are placing their arm and hand underneath the prosthetic hand in a similar position and are asked to concentrate on the virtual hand. This means if virtual hand position is noticeably wrong (e.g., palm facing upwards) it could disrupt embodiment. A category to account for this was added noting if the general hand position was correct.

A further category was added after additional experience with Leap Motion where in some cases it was noticed that fingers displayed occasional flickering. Unlike the incorrect movement of individual fingers category, this involves a rapid flickering of a finger (usually just the fingertip) where it briefly moves position and then returns to original position. This may not disrupt embodiment as much as other categories but could still have an influence or distract participants so was decided to include to see how common it occurred and if any noticeable difference between conditions.

For both correct movement of fingers and fingers not flickering 2 “levels” of analysis are included – 1) a deeper level involves noting the exact number of fingers for each category, and 2) a general level involves noting whether or not any of the fingers displayed each category and not referring to the exact number of fingers (explained further below). The general level allows for this to be included in the overall accuracy calculation (an average of all the categories) whereas the deeper analysis is useful to see the extent of any issues with those categories (e.g., 5 fingers moving incorrectly could be considered more significant an issue than 1 finger). The general level is a stricter form of analysis as all 5 fingers need to be “correct” for that category to be noted as accurate.

As previously, videos were analysed using Tracker 4.96 (Open Source Physics). Videos were filmed in high frame rate the same as for the latency analysis (100fps) so individual frames can be checked in the software to identify when the prosthetic hand and virtual were beginning to open, close, or stop movement. As before, 10 movements were made (5 closing, 5 opening) but additionally it was decided to analyse the period of time between each movement when the hand was still. Whilst the synchrony of time between

movement and observing movement is the key factor in embodiment any inaccuracy between the movements (i.e., when the hand is still) could disrupt the overall perception of the virtual prosthesis (e.g., if it vanishes or switches to a left hand). Analysis begins with the first movement of the hand closing from an open position and ends with the final hand opening movement which makes 9 periods of the hand remaining still for a total of 19 “stages” of analysis. Moments of the hand remaining still either side of the first and last moment were filmed but not included in the analysis as the length of time for these was largely variable. Also, in experiments the period in which embodiment is expected to start is after the stimulation begins (i.e., hand movements). The following acronyms are used in the analysis to represent the movements:

- *HDC* = myoelectric hand closing (i.e., the period in which the hand is closing).
- *HDO* = myoelectric hand opening (i.e., the period in which the hand is opening).
- *HS* = myoelectric hand still (i.e., the period in which the hand is not opening or closing).

Also, the following descriptive labels and definitions for relevant codes for individual accuracy categories representing for behaviour of the virtual hand are:

- *Virtual hand present* = the virtual hand is displayed (coded as 1 = present for whole time, 0 = not present at least some of the time).
- *Virtual hand correct* = the virtual hand is displayed as a right hand (coded as 1 = correct for whole time, 0 = not correct at least some of the time).
- *Virtual hand correct position* = the virtual hand is displayed in the generally same position as the prosthetic hand (coded as 1 = correct position for whole time, 0 = not correct position at least some of the time).
- *Virtual hand appropriate movement* = the virtual hand movement is relevant to the movement of the myoelectric hand, either opening, closing, or remaining still (coded as 1 = generally displays the appropriate movement, 0 = no movement in the appropriate direction or movement when the prosthetic hand is still).
- *Number of correct virtual fingers* = the number of fingers/thumb which display noticeably correct movement such as moving the correct direction or not moving when the hand is still (coded as 1/2/3/4/5 = the number of fingers/thumb which move correctly, 0 = no fingers/thumb move correctly).

- *Correct virtual fingers* = the fingers/thumb move correctly (see above) (coded as 1 = all the fingers move correctly, 0 = at least 1 finger/thumb moves incorrectly).
- *Number of virtual fingers not flickering* = the number of fingers/thumb which do not display flickering while moving or staying still (coded as 1/2/3/4/5 = the number of fingers/thumb which do not flicker at all – those which flicker part of the time are not counted, 0 = all fingers/thumb flicker at least part of the time).
- *Virtual fingers not flickering* = the fingers/thumb do not flicker (see above) (coded as 1 = all the fingers/thumb do not flicker, 0 = at least 1 finger/thumb flickers).

Separate spreadsheets were used for each combination of conditions. Overall averages for hand movements were assessed along with separating hand closing and opening movements in case accuracy differs between these. See Table V8 for summary of analysis.

Table V8

*Accuracy of Leap Motion accuracy analysis*

	Latency mode		Accuracy mode		Average
	Thumb off	Thumb on	Thumb off	Thumb on	overall
	base %	base %	base %	base %	%
Not head mounted	93.86	80.70	92.98	64.04	82.90
Is head mounted	99.12	77.19	95.61	71.93	85.96
Average percentages	96.49	78.95	94.30	67.99	84.43
Average overall %	87.72		81.14		

## Appendix W: Demo development for VR study

### Developing demo

For use in planned IVR experiments a VR demo has needed to be built, alongside learning various pieces of software and hardware to create and run the demo. The general appearance of this is vital as a first-person perspective is necessary for using techniques to induce body ownership. Various software and hardware are being used across the development of the demo:

Hardware.

- 1) Oculus Rift DK2 HMD.
- 2) Leap Motion device.
- 3) PC.
- 4) Laptop.

Software.

- 1) Unity.
- 2) Leap Motion.
- 3) Make Human
- 4) Blender.

#### **Initial development.**

After learning to use Unity, an initial scene of a room was built with a carpeted floor. Assets (individual files which can be downloaded and imported into a project) were searched on the Unity store for a suitable table and chair. These were then resized and positioned in the demo.

#### **Avatar development.**

Software to create avatars, *Make Human*, was identified. I had to learn how to use this software and then created an avatar for my scene. However, the avatar is standing up and needed to be sitting down position to fit on the chair and table. *X-box Kinect* was considered and briefly explored to potentially motion track me in a sitting down position and then fit the created avatar to this position. This became problematic, getting the avatar to match a natural

position however I explored the use of animation program Blender to animate the avatar into a sitting position. This involves manually rotating various bone segments of the avatar to the desired position. This can then be imported into Unity and checked if it is in a suitable position. Various testing of the overall perspective was completed by altering the position of the virtual camera to be in a natural position for the avatar's perspective in looking down at the body and table.

### **Leap Motion development.**

After various explorations with the Leap Motion software and hardware working virtual hands were implemented into my demo with the Leap Motion device attached to the Oculus Rift. This was with a basic wireframe type hand that is the default hand for the software. After further exploration I managed to get a more solid looking hand and lower arm (as shown in photos of the latency and accuracy testing).

### ***Further Leap Motion development - the use of older core assets.***

Initial latency and accuracy testing were completed with a basic hand appearance suitable for testing but not for final demo. Initial testing used the latest software for tracking and the latest software for VR development (Leap Motion Orion assets). The virtual hand used in the demo needs to reflect a virtual prosthesis and also of altering appearance. It was found that the Orion assets only contain very limited hand appearances which are largely not suitable. However, after a detailed exploration through online sources (searching for videos displaying hand types not available in Orion assets, comments on official Leap Motion Orion assets posts, general discussion on Leap Motion hands etc.) a lot of discussion was found regarding previous versions of Leap Motion assets having a much larger variety of hands available (e.g., on the Leap Motion community forum - <https://community.leapmotion.com/>). So, this was pursued as a possible alternative.

After finding older version of the core assets I had to learn how to set up the leap motion rig in Unity as this is different than with Orion assets. Through exploring this, I managed to find a variety of older hands including a couple of robotic type hands and realistic human hands. However, a problem was encountered with editing in Unity as after opening the demo it would only play once and then cut the signal to the Oculus Rift HMD. This means hands could be visualised within the environment I was building but repeated editing of the demo was impossible without exiting Unity after each edit, re-entering demo,

and then checking in the HMD. This is impracticable so I explored various ways to try resolving this by searching online, but couldn't reach a solution. This involved an in-depth 'trial and error' approach making step by step changes to the demo or settings in Unity. Ultimately, I was unable to resolve issues with the old software it was decided to proceed with the new software.

### ***Further Leap Motion development - the use of a different Leap Motion rig.***

Through testing, I became concerned about accuracy of prosthetic tracking if participants have free movement of HMD with the Leap Motion device attached. This is because the HMD with Leap Motion attached often needed to be positioned in a certain way to capture the prosthetic hand correctly before filming. With free head movement there would be no way to control this. So following suggestion from Argelaguet et al. (2016) I re-built a new Leap Motion rig with the device not attached to the HMD but looking downwards still. This involved a lot of manipulation within the demo as virtual hands and first-person perspective camera are set up differently. Also, the physical position of the Leap Motion device needs to be in an exact fixed location relative to the hand being captured. After creating a temporary physical rig to hold the leap Motion device out of cardboard for testing a sturdier and professional looking rig was made from a metal bar covered in the same antireflective tape used on the base.

### ***Introducing delays into the Leap Motion hands.***

To introduce a fixed delay (i.e., they will move and specific number of frames later than actual hand movement) into the hands specific scripts needs to be altered or added into existing scripts in the software. This was achieved for the old version of Leap Motion assets but getting this to work in the current software is problematic as a lot of the scripts have changed with the updated software. This is another reason why the old Leap Motion software would be desirable to use if it did not suffer from technical issues.

### **Further changes – creating an amputee avatar and perspective suitable for experiment.**

It was decided to build the demo on the laptop to aim to improve latency and accuracy and explore specific conditions which might influence either of them. Also, there was concern about seeing the disembodied arm which Leap Motion provides. After various explorations to avoid seeing a disembodied arm it was decided the best solution was to have

the first-person perspective avatar positioned next to the virtual arm. To achieve this, I had to learn how to create an altered avatar in the program Blender, to represent an amputee avatar. This involved positioning the arm in an appropriate place so that it would be resting on the table in the demo (a process of trial and error) and then manually deleting parts of the arm bit by bit and testing with the Leap Motion arm. In addition to this additional Leap Motion hand appearances were explored to see what is possible with the new version of the software. I have tried applying textures to the Leap Motion hand to approximate varying appearances of a prosthesis. Also, the wire frame type hand is planned to be used in the practice session in experiments

**Current progress.**

The demo is currently being developed further exploring introducing delays, various additional appearances of the virtual arm, and exploring creation of a virtual threat.



## Appendix X: Questionnaire qualitative responses for VR study

### X.1 Questionnaire responses for the hand condition

Table X1

*Questionnaire response data for the hand condition*

Participants	1	2	3	4	5	6	7	8	9	0	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	3	3	
Unnatural	1																																<b>1</b>
Felt realistic/More realistic to control than electrodes/felt hand controlling prosthesis	1													1				1					1							1	1	<b>6</b>	
Felt like controlling hand in a game, aware not my hand		1								1																						<b>2</b>	
Easy to control/Easier to control than with electrodes																						1										<b>2</b>	
Felt comfortable																																<b>1</b>	
Easier to believe hand was mine than prosthetic condition																																<b>2</b>	
Shaking stopped hand feeling like my hand																																<b>1</b>	
Limited speed, smoothness, flexibility stopped hand feeling like my hand																																<b>1</b>	
Limited speed of hand																																<b>1</b>	
Limited smoothness of hand	1																															<b>2</b>	









Felt as if sat in the virtual room	1									1
Like controlling a game			1							1
It felt strange at beginning				1						1
It felt strange						1		1		2
Will of my mind to make it move/I felt I was controlling everything by my mind					1				1	2
Enjoyed experience	1								1	2
Felt realistic		1								1
I felt like I was trying to move a mechanical hand								1		1
Lower fingers lagged behind hand movement				1						1
The closing felt natural and looked as it was my hand, the opening was odd because the virtual hand did not go back as far as mine								1		1
Thumb shaking was a little distracting and didn't reflect what I could feel									1	1
Bit worried about knife hurting hand										1

**Appendix Y: Data from qualitative responses to additional questions after the  
experiment**

**Y.1 Question 1: Awareness of accuracy data responses**

Table Y1

*Question 1: Awareness of accuracy*

Participant								If noticed and gave info				
	Yes	Yes (prosthetic)	Yes (hand)	A little	A little (prosthetic)	A little (hand)	No	Flickering	Moving incorrectly	Vanish into table	Hand flipping	Latency
3	1	0	1	0	0	0	0	0	0	0	0	0
4	1	0	0	0	0	0	0	0	0	0	1	0
5	0	0	0	0	0	0	1	0	0	0	0	0
6	1	0	0	0	0	0	0	0	0	0	0	0
7	1	1	1	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	1	0	0	0	0	0
9	0	0	0	1	0	0	0	1	0	0	0	0
10	1	0	0	0	0	0	0	1	1	0	1	0
11	1	0	1	0	0	0	0	0	1	0	0	1
12	1	0	0	0	0	0	0	0	1	0	0	0
13	0	0	0	1	0	0	0	0	1	0	0	0
14	1	0	0	0	0	0	0	0	1	0	0	0
15	1	0	1	0	0	0	0	0	1	0	0	0
16	1	0	0	0	0	0	0	0	1	0	0	0
17	1	0	0	0	0	0	0	0	0	0	0	0
18	1	0	0	0	0	0	0	0	0	0	0	0
19	0	0	0	1	1	0	0	0	0	0	0	0
20	0	0	0	1	0	0	0	0	0	0	0	0
21	1	0	1	0	0	0	0	0	1	0	0	0
22	1	1	1	0	0	0	0	0	1	0	0	0
23	1	1	1	0	0	0	0	0	1	0	0	0
24	1	0	0	0	0	0	0	0	0	0	0	0
25	1	0	0	0	0	0	0	0	0	0	0	0
26	1	1	0	0	0	0	0	0	0	0	0	0
27	1	0	0	0	0	0	0	0	0	0	0	0
28	1	0	1	0	0	0	0	0	0	0	0	0
29	1	0	0	0	0	0	0	1	0	0	0	0
30	1	0	1	0	0	0	0	0	1	0	0	0
31	0	0	0	1	0	1	0	0	0	0	0	0
%	75.86	13.79	31.03	17.24	3.45	3.45	6.90	10.34	37.93	3.45	3.45	3.45

## Y.2 Question 2: Impact of accuracy data responses

Table Y2

Question 2: Impact of accuracy

Participant											If noticed and gave info				
	Yes	Yes (ownership)	Yes (agency)	Yes (prosthetic)	Yes (hand)	A little	A little (prosthetic)	A little (hand)	No	Flickering	Wrong place	Vanish into table	Hand flipping	Latency	
3	1	0	0	0	0	0	0	0	0	1	0	0	0	0	
4	0	0	0	0	0	0	0	0	1	0	0	0	0	0	
5	0	0	0	0	0	0	0	0	1	0	0	0	0	0	
6	0	0	0	0	0	0	0	0	1	0	0	0	0	0	
7	1	1	0	0	0	0	0	0	0	0	0	0	0	0	
8	0	0	0	0	0	0	0	0	1	0	0	0	0	0	
9	0	0	0	0	0	0	0	0	1	0	0	0	0	0	
10	1	0	0	0	1	0	0	0	0	0	0	0	0	0	
11	1	0	0	0	0	0	0	0	0	1	0	0	0	1	
12	0	0	0	0	0	1	0	0	0	0	0	0	0	0	
13	0	0	0	0	0	0	0	0	1	0	0	0	0	0	
14	0	0	0	0	0	1	0	0	0	0	0	0	0	0	
15	0	0	0	0	0	1	0	0	0	0	0	0	0	0	
16	0	0	0	0	0	1	0	0	0	0	0	0	0	0	
17	0	0	0	0	0	0	0	0	1	0	0	0	0	0	
18	0	0	0	0	0	1	0	0	0	0	0	0	0	0	
19	0	0	0	0	0	0	0	0	1	0	0	0	0	0	
20	0	0	0	0	0	0	0	0	1	0	0	0	0	0	
21	1	1	0	0	0	0	0	0	0	0	0	0	0	0	
22	0	0	0	0	0	0	0	0	1	0	0	0	0	0	
23	0	0	0	0	0	0	0	0	1	0	0	0	0	0	
24	0	0	0	0	0	0	0	0	1	0	0	0	0	0	
25	0	0	0	0	0	0	0	0	1	0	0	0	0	0	
26	1	0	0	0	0	0	0	0	0	0	0	0	0	0	
27	1	0	0	0	1	0	0	0	0	0	0	0	0	0	
28	1	0	1	0	0	0	0	0	0	0	0	0	0	0	
29	0	0	0	0	0	1	0	0	0	0	0	0	0	0	
30	0	0	0	0	0	1	0	0	0	0	0	0	0	0	
31	0	0	0	0	0	0	0	0	1	0	0	0	0	0	
%	27.59	6.90	3.45	0.00	6.90	24.14	0.00	0.00	48.28	3.45	3.45	0.00	0.00	3.45	



### Y.3 Question 3: Impact of hand placement data responses

Table Y3

*Question 3: Impact of hand placement*

Participant				Reason given		Suggestions to improve
	Yes	A little	No	Harder to control prosthesis under table	See hand on table and feel it	Rest hand on something over leg
3	0	0	1	0	0	0
4	0	0	1	0	0	0
5	0	0	1	0	0	0
6	0	0	1	0	0	0
7	0	0	1	0	0	1
8	0	0	1	0	0	0
9	0	0	1	0	0	0
10	0	0	1	0	0	0
11	0	0	1	0	0	0
12	1	0	0	1	0	0
13	0	0	1	0	0	0
14	0	0	1	0	0	0
15	0	1	0	0	1	0
16	0	0	1	0	0	0
17	0	0	1	0	0	0
18	0	0	1	0	0	0
19	0	0	1	0	0	0
20	0	0	1	0	0	0
21	0	1	0	0	1	0
22	0	0	1	0	0	0
23	0	0	1	0	0	0
24	0	0	1	0	0	0
25	1	0	0	1	0	0
26	0	0	1	0	0	0
27	1	0	0	0	1	0
28	0	0	1	0	0	0
29	0	0	1	0	0	0
30	0	0	1	0	0	0
31	0	0	1	0	0	0
%	10.34	6.90	82.76	6.90	10.34	3.45

#### Y.4 Question 4: If the knife was a threat data responses

Table Y4

Question 4: If the knife was a threat

Participant	Reason given for not a threat										How to improve						
	Yes	Yes (prosthetic)	Yes (hand)	A little	No	Not realistic	Knew hand or knife was not real	Slow	Thought had to pick it up or dodge	No sound	Stab hand	Multiple knives	Sound	Quicker	Larger	Different position	Vibration
3	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	1	1	0	0	0	1	0	0	0	0	0	0	0
5	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	1	1	0	1	0	0	0	0	0	0	0	0	0
8	0	0	0	0	1	0	1	0	0	1	0	0	0	0	0	0	0
9	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
13	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14	0	0	0	0	1	0	0	0	1	1	0	0	0	0	0	0	0
15	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	1	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0
17	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
18	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0
19	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
21	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0
22	0	0	0	0	1	0	1	0	0	0	0	1	1	0	0	0	0
23	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24	0	0	0	1	0	0	0	1	0	0	0	1	1	1	0	0	0
25	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
26	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
27	0	0	0	1	0	0	1	0	0	0	0	1	1	0	0	0	0
28	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0
29	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	1	0
30	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
31	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
%	34.48	10.34	20.69	13.79	51.72	10.34	17.24	6.90	6.90	3.45	6.90	3.45	17.24	10.34	3.45	3.45	3.45