Characterizing the Visuomotor Behaviour of Upper Limb Body-Powered Prosthesis Users

by

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Abstract

In recent years, significant research attention in the field of upper limb myoelectric prostheses has focused on improvements in control and integration of sensory feedback, which is hoped to reduce the visual attention and cognitive demand of operating these devices. However, there is currently no standard protocol for assessing the efficacy of these innovations by quantifying their impact on a user's visuomotor behaviour. Furthermore, the visuomotor behaviour of individuals using prevailing upper limb prosthetic technologies (namely, body-powered prostheses) is not well understood. The primary objective of this thesis work was to characterize the visuomotor behaviour of a sample of body-powered prosthesis users to better understand current demands of traditional prostheses, as a future comparator to emerging prosthetic technologies.

Five transradial body-powered prosthesis users and three transhumeral body-powered prosthesis users completed two functional upper limb tasks while their eye gaze behaviour and movement patterns were tracked using motion capture and eye-tracking technologies. Combined data from these systems was analyzed using a custom software tool that allowed for automatic and precise quantification of a number of outcome metrics relating to task performance, eye gaze behaviour, eye-hand coordination and quality of movement. Results for each body-powered prosthesis user were compared to a set of normative outcomes previously established under the same experimental protocol for twenty able-bodied individuals.

Relative to the normative data set, trends in behaviour emerged across the body-powered prosthesis users. The body-powered prosthesis users consistently took longer to complete the tasks and exhibited decreased end effector movement quality, as evidence by increased numbers of movement units. The prosthesis users also tended to dedicate more visual attention to their terminal device, especially after picking up an object, and occasionally while reaching for an object. However, while transporting an object,

they would eventually transition their gaze to the object drop-off location before their terminal device arrived there, and not glance back and forth between this target and their terminal device in flight.

Despite similarity in behavioural trends across the body-powered prosthesis users, there was variability between them which revealed differences in skill level, strategies, and level of amputation. Differences between the two upper limb tasks also appeared to elicit different visuomotor behaviours and pose unique challenges for individuals with different levels of amputation.

Further data collection is required to increase the sample size, and improve understanding of how the behaviour described in this thesis compares with other prosthesis user populations, such as myoelectric prosthesis users. However, these findings on the visuomotor behaviour of body-powered prosthesis users, and the technical development undertaken to accomplish this analysis, represent an important contribution. This work will be useful in assessing the efficacy of current and future innovations in upper limb prosthesis technology, which should in turn help to improve the state of technology available to individuals with upper limb loss.

Preface

The research project, of which this thesis is a part, received research ethics approval from the University of Alberta Research Ethics Board (Pro00054011), the Department of the Navy Human Research Protection Program (DON-HRPP), and the SSC-Pacific Human Research Protection Office (SSCPAC HRPO).

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This thesis is an original work by Quinn Boser. No part of this thesis has been previously published.

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Glossary of Symbols and Terms

<: Less than

>: Greater than

%: Percent

2D: Two-dimensional

3D: Three-dimensional

ACMC: Assessment of Capacity for Myoelectric Control

AM-ULA: Activities Measures for Upper Limb Amputees

AOI: Area of Interest

BP: Body-powered

EAL: Eye Arrival Latency

ELL: Eye Leaving Latency

G: Grasp

Hz: Hertz

M: Movement

mm: Millimeter

ms: Milliseconds

R: Reach

RL: Release

s: Seconds

SD: Standard Deviations

SHAP: Southampton Hand Assessment Procedure

T: Transport

TLS: Target Locking Strategy

TR: Transradial

TH: Transhumeral

Chapter 1. Introduction

1.1 Problem Statement

Upper limb loss has a significant impact on an individual's quality of life and independence, and it is critical that those with upper limb loss are provided with effective solutions that allow them to function independently for their lifetime. To this end, a great deal of effort in recent decades has been directed at improving the dexterity and functionality of electrically powered upper limb prostheses (Burck et al. 2011). However, rejection rates for these devices remain around 20% or higher (E. Biddiss & Chau 2007), and many individuals still choose traditional body-powered devices over newer technologies (Østlie et al. 2012). High demand for visual attention while operating the prosthesis is often cited as an area where improvement is desired (Cordella et al. 2016) and where body-powered prostheses may offer an advantage, through feedback inherent to the control cables (Carey et al. 2015). While efforts to improve electrically powered upper limb prostheses continue through advancements such as new control strategies and integration of sensory feedback (White et al. 2017; Schofield et al. 2014), there is a need for more sensitive outcome metrics to assess the efficacy of these new technologies (Wang et al. 2018).

Eye tracking and motion capture are promising tools for assessing upper limb prostheses by quantifying prosthesis user visuomotor behaviour. However, there is currently no standardized upper limb assessment protocol that leverages eye and motion tracking technologies. Furthermore, the visuomotor behaviour of individuals using prevailing technologies (specifically body-powered upper limb prostheses) has not been investigated or well characterized, as most research focuses on advanced myoelectric devices. This thesis aims to address the gap in the literature pertaining to eye gaze behaviour of upper limb body-powered prosthesis users, and was undertaken as part of a larger effort to establish novel assessment metrics of upper limb prosthesis functionality.

1.2 Objectives

The focus of this thesis is on characterizing the visuomotor behaviour of body-powered prosthesis users during the performance of goal directed, object manipulation tasks. The specific objectives of this thesis were to: 1) examine the eye gaze behaviour, eye-hand coordination and end effector movement quality of five transradial body-powered prosthesis users in comparison to a set of able-bodied individuals; 2) extend the analysis to three transhumeral body-powered prosthesis users, and carry-out a preliminary comparison between the transradial and transhumeral user participants; and 3) conduct a preliminary comparison of findings from the present study with literature on the visuomotor behaviour of transradial myoelectric prosthesis users.

1.3 Chapter Summary

Chapter 2 of this thesis provides an overview of background knowledge and literature that is relevant to the stated objectives. This chapter will begin with general information on upper limb loss, the epidemiology of the affected population, and current technologies available for upper limb prosthesis users. This is followed by an overview of current assessments for upper limb prosthesis functionality and their associated limitations. Finally, a relevant summary of experimental findings related to eye gaze behaviour and end effector movement of able-bodied individuals and upper limb prosthesis users is presented.

Chapter 3 provides a detailed description of the methods employed to accomplish the project objectives, including the experimental protocol and data analysis methodology. As part of this chapter, details are provided on the technical development of a custom software tool which was used to perform integrated analysis of eye gaze and movement behaviour.

In Chapter 4, the results of the experiment and analysis are presented, including outcome metrics describing the eye gaze behaviour and end-point kinematics of five transradial and three transhumeral body-powered prosthesis users for two upper limb functional tasks.

Chapter 5 provides a detailed discussion of the results presented in Chapter 4; how they are informed by characteristics of the participants and their prosthetic devices; how they may inform the future application and interpretation of these outcome metrics; and how they compare with findings in the literature. An examination of the limitations of this study is also included.

Chapter 6 includes a discussion of future work as well as final remarks.

Chapter 2. Literature Review

2.1 Upper Limb Amputation and Prosthesis Use

An upper limb (UL) amputation involves the absence or removal of all or part of the fingers, hand or arm. UL amputation may be congenital (present at birth) or the result of a surgical procedure in response to trauma or disease (Smith et al. 2004). Major UL amputation is generally considered to include amputations at or proximal to the wrist (Smith et al. 2004).

Since data on the prevalence of UL amputation in Canada have not been well reported, estimates of the number of individuals affected by UL loss are often inferred from other population studies. In the United States, as of 2008, there were over 40,000 people living with major UL loss (Ziegler-Graham et al. 2008). In addition, according to the U.S. Department of Health and Human Services, over the 15 year period from 2000 to 2014, an average of 1107 new cases of major UL amputation occurred per year (accessed via the Healthcare Cost and Utilization Project (Anon n.d.)). The majority of UL amputations are caused by trauma (Ziegler-Graham et al. 2008), which primarily affects young (under 45), otherwise healthy individuals (Dillingham et al. 1998; Nghiem et al. 2015). Consequently, it is common for an individual to live with upper limb loss for many decades, and the cumulative impact on their well-being can be quite high. Thus, it is in the best interest of both these individuals and society that they be provided with effective solutions that not only allow them to remain independent and productive members of society, but also help prevent future complications.

UL prosthetic devices are available in two broad categories: passive and actively controlled (Lake & Dodson 2006). Passive prostheses do not allow active control of any movements of the prosthetic joints, and often serve as stabilizers during object manipulation and as cosmetic devices. Active prostheses allow active control of prosthesis joint movement by the wearer, and are further divided into body-powered and externally powered devices (Lake & Dodson 2006). Body-powered prostheses use a harness and cables to transfer the user's body movement (usually movement of the shoulder complex) into movement of the prosthesis. Externally powered prostheses make use of electrical components (i.e., batteries, motors) to power and actuate the prosthesis. To control an externally powered prosthesis, the user typically signals their intentions to an on-board microprocessor via surface electromyography (EMG) sensors placed over the residual limb muscles. The microprocessor then interprets these signals and controls the movement of the prosthetic components. Due to the nature of their control strategy, externally powered prostheses are typically referred to as myoelectric prostheses.

It has been estimated that, of the individuals who are fitted with an UL prosthesis, approximately 20% subsequently reject the use of the device (use it once a year or less) (E. Biddiss & Chau 2007; E. A. Biddiss & Chau 2007). Specific rejection rates vary depending on factors such as: level of amputation, gender, and age (E. Biddiss & Chau 2007). With respect to level of amputation, Biddiss and Chau found that individuals with an amputation proximal to the elbow were more likely to reject their prosthesis than those with a transradial amputation. The primary factors that contribute to prosthesis rejection include discomfort, difficulty of control, and a lack of sensory feedback from these devices (E. Biddiss & Chau 2007; Cordella et al. 2016). As a result of the lack of sensory feedback provided by UL prosthetic devices, prosthesis users also report that these devices require a large amount of their visual attention (Atkins et al. 1996; Cordella et al. 2016), which many consider burdensome.

Of those individuals who choose to use an actively controlled UL prostheses, roughly half still prefer a body-powered device over newer myoelectric technology (E. Biddiss & Chau 2007; Kyberd & Hill 2011; Østlie et al. 2012). The advantages of body-powered prostheses over myoelectric include increased durability, lighter weight and more moderate cost (Lake & Dodson 2006). Experts have also speculated that one reason body-powered devices remain popular despite the introduction of more advanced technology is that their cable control system offers some level of grip strength and proprioceptive feedback to the user (Antfolk et al. 2013; Nghiem et al. 2015; Carey et al. 2015). Although commercially available myoelectric prostheses do not currently have any mechanism for providing sensory feedback to their users, work is ongoing in this area. Recent efforts have focused on providing tactile and kinesthetic feedback from an upper limb prosthesis to the user (Antfolk et al. 2013; Tyler 2016; Marasco et al. 2018). Other efforts have focused on relieving the cognitive burden associated with operating myoelectric prostheses by improving the ease of control (Deeny et al. 2014; White et al. 2017). However, to date, only a limited number of these innovations have demonstrated a significant level of efficacy in real-word applications or been integrated into commercially available prostheses (Antfolk et al. 2013). Furthermore, there is little consensus on how best to determine the efficacy of these technologies or the functionality of a user with a given device, as standard assessments for UL prosthetic device functionality have not kept up with the rapid developments in technology.

2.2 Upper Limb Prosthetic Device Assessment

Assessment is a critical step in the development process of any new technology. In the case of prosthetic device technology, effective, unbiased assessment is especially important as results may be used not just by developers, but in regulatory and clinical decisions as well as to justify the costs of these technologies to funding and reimbursement agencies. However, in the field of UL prosthetic device development, there is little agreement on the most appropriate way to effectively assess new technologies.

In 2005, a group of professionals in the field of UL prosthetic device development set up a working group to examine the state of UL prosthesis assessment and create a set of recommendations (Hill et al. 2009). This group identified a number of issues in the methods being used to assess UL prostheses, including a lack of: clear definitions, a standardized approach, and adequate validation of many of the commonly used assessments. Hill et al. put forth a toolkit of recommended UL assessments; however, the majority of their recommended outcome measures were based on observation or self-rating, which can be susceptible to bias (Wang et al. 2018). In a more recent review, Wang et al. (2018) focused on objective performance-based UL outcome measures, and noted a need for measures that assess sensation and quality of movement. Upper limb assessments with quantitative outcomes have generally focused only on how quickly a task can be performed, which may not be informative of advantages offered by technologies like sensory feedback.

One example of a commonly used “speed based” test is the Box and Blocks Test (Mathiowetz et al. 1985), which, although not validated for the UL prosthesis user population (Wang et al. 2018), is commonly used to assess UL prosthesis functionality. The Box and Blocks Test is a measure of how many rigid blocks an individual can move from one side of a box, over a barrier, to the other side in a pre-set time frame. A recent study on the benefits of artificial feedback for prosthesis users found that performance for the Box and Blocks Test did not benefit from additional feedback (Markovic et al. 2018). The authors attributed this to the simplicity of the task and time-based outcome metric. While it has been shown that task completion time is a critical outcome that relates to prosthesis user skill level (Bouwsema et al. 2012), it does not deliver a complete representation of functional ability. Hence, in the same study it was argued that a combination of outcome measures should be used to gain maximal insight when assessing prosthetic technologies (Bouwsema et al. 2012). Hebert and Lewicke (2012) provided further support for this position when they used a modified version of the Box and Blocks Test with motion capture (Hebert, Lewicke, et al. 2014) to compare one individual’s level of functionality with a body-powered prosthesis and a myoelectric prosthesis. In this case study, Hebert and Lewicke showed that while this individual was roughly two times slower when using the myoelectric prosthesis, they also used less compensatory movements. Therefore, by considering only their time related performance, one might have concluded that this individual was less functional with the myoelectic prosthesis and failed to recognize the functional benefits associate with the reduction in compensatory movement. However, Hebert and

Lewicke were not able to attribute whether the reduction in speed with the myoelectric prosthesis was associated with a reduction in sensory feedback. In fact, as Wang et al. (2018) noted, there is a lack of validated UL prosthesis outcome measures that include a sensation component, despite the recent focus on restoring sensation in prosthesis users.

In the absence of validated outcome measures for sensory feedback systems, many researchers have devised their own assessments. These often involve participants performing various tasks while they are blindfolded or in the dark. Such tasks have included: pulling the stem off a cherry without squishing it (Tyler 2016), detecting the presence of a rubber ball, foam block, or wooden block while closing their terminal device (Hebert, Olson, et al. 2014; Schiefer et al. 2016), and modified versions of the Box and Blocks test (Schiefer et al. 2016; Raveh et al. 2018). These studies using visual obscuration have shown that additional sensory feedback (e.g. vibrotactile, electrical) can improve task performance in the absence of visual feedback. However, this does not necessarily indicate that the added feedback is useful enough to alleviate the visual demand and cognitive burden associated with these devices in more functional real-world circumstances. The experimental model of obscuring vision does not allow experimenters to prove that these prosthesis users would not find visual feedback to be more reliable than the sensory feedback if it was available to them.

One approach that has been considered to assess visual requirements of a task without artificially obscuring vision is to monitor patterns of gaze behaviour during performance of functional tasks. This tactic is motivated by testimony from prosthesis users indicating that current UL prosthetic devices place a high demand on their visual attention (Atkins et al. 1996; Cordella et al. 2016). The Assessment of Capacity for Myoelectric Control (ACMC) (Hermansson et al. 2005) is an assessment that was recommended by Hill et al. (2009) and employs this strategy by including a scoring component for the extent to which an individual can perform object manipulation without visual feedback. However, the ACMC has only been validated in myoelectric prosthesis users and is not valid for use with body-powered prosthesis users. In addition, the ACMC is scored by a trained human evaluator who must carefully watch an individual perform a functional task with their prosthetic device. Consequently, this assessment is time consuming for therapists to administer, and the results have a subjective component.

Modern head-mounted eye tracking technology has presented a means by which to quantitatively evaluate eye gaze behaviour during functional task performance (Lavoie et al. 2018). In general, these devices include one or two cameras directed at the wearer’s eye(s) and one scene camera directed forward. The accompanying software uses the feed from the eye camera(s) to track the wearer’s pupil position(s), which are used in conjunction with a calibration to predict the focus on their gaze in the forward-facing scene camera. This prediction is overlaid on the scene camera video, so that the point of gaze can be classified into task-relevant areas of interest (e.g., hand, object, etc.), which is usually analyzed frame-by-frame by the researcher.

A number of studies have employed eye tracking technology to study the behaviour of individuals using prosthetic devices (Bouwsema et al. 2012; Sobuh et al. 2014; Chadwell et al. 2016; Raveh et al. 2017; Parr et al. 2017), the results of which will be discussed in section 2.3.2. These studies generally show that individuals using myoelectric upper limb prostheses tend to demonstrate more hand focused patterns of gaze behaviour compared with able-bodied individuals. However, there is currently no standardized UL assessment protocol making use of eye tracking technology that has been validated as to consistency and repeatability in prosthesis users. Consequently, these studies have used a variety of different assessment tasks and outcome measures, making it difficult to compare between them. This lack of standardized assessment protocols presents a challenge to effective summarizing and comparing of results in this field (Hill et al. 2009).

2.3 Visuomotor Behaviour

2.3.1 Eye Gaze Behaviour in Able-Bodied Individuals

Over the last century, much work has been directed at characterizing natural eye gaze behaviour (Land 2006). Until the 1980s, available technology only supported the monitoring of eye behaviour while the head was held stationary (Land 2006). Since head-mounted eye tracking technology became commercially available in the 1980s, it has been used to study eye gaze behaviour in a wide variety of tasks, from rearranging blocks (Ballard et al. 1992) and preparing food (Land et al. 1999; Hayhoe 2000) to driving and playing ball sports (Land 2006). Across this wide array of activities, a number of common characteristics of eye gaze behaviour have been observed.

For the most part, natural eye gaze behaviour consists of a strategy of fixations and saccades, where fixations are periods of time when the eyes are relatively still and information is taken in, and saccades are quick eye movements to transition between fixation points (Land 2006). This strategy has been observed in the majority of activities studied. Even tasks where we might subjectively feel that our eyes are moving smoothly (reading this line of text, for example), are really accomplished using a series of short fixations and saccades (Rayner 1998). The main exception is that when tracking small moving objects, we are able to employ a strategy of smooth pursuit, so long as the object is not moving too quickly (slower than 15°/s according to Land 2006).

Another characteristic of eye gaze behaviour which has been well documented is that, during purposive tasks, eye gaze generally precedes action by up to one second. For example, when reading aloud, high school students were observed to vocalize a syllable an average of 0.79 s after they had fixated on it (Buswell 1920). Similarly, when copy typing, individuals at a range of skill levels maintained a time difference of approximately 1 s between fixating a specific letter and typing it themselves (Butsch 1932). Studies using head-mounted eye tracking have found similar results with respect to eye gaze leading action. In 1999, Land et al. studied the eye gaze behaviour of three individuals while they made tea, and found that, throughout this task, participants fixated on objects an average of 0.56 s before they began to manipulate them. Land et al. also noted that these individuals did not tend to keep their gaze on an object for the entire time during manipulation; instead, they moved on to their next object of interest an average of 0.61 s before their current action was complete. There has been one activity in which this gaze leading behaviour was not observed: during learning of a new motor task. Sailer et al. (2005) found that, while participants were learning to use a novel apparatus for controlling a cursor on a screen, they underwent a learning period where they tended to monitor the cursor with their gaze. Only once participants had had time to become comfortable with the control scheme did they begin to anticipate the cursor's future position with their gaze.

When looking at the eye gaze behaviour of individuals performing goal-directed tasks, it has consistently been noted that able-bodied individuals rarely fixate on task irrelevant objects or their hands. Both Land et al. (1999) and Hayhoe (2000) separately made these observations while studying tasks of tea making and peanut butter and jelly sandwich preparation, respectively. In both of these tasks, it was found that less than 5% of eye gaze fixations were to task-irrelevant objects, despite the presence of many "potential distractors" especially in the tea making environment (Land & Hayhoe 2001). Both authors also observed that their participants rarely fixated their gaze on their hands, and often discontinued fixations on objects their hands had made contact with. They attributed this behaviour to a shift from reliance on visual feedback to touch and proprioception (Land & Hayhoe 2001).

In a more recent study, Lavoie et al. (2018) used a combination of motion and eye tracking to automate the process of eye tracking analysis in order to characterize the behaviour of 20 able-bodied individuals performing 20 repetitions of two unilateral, goal-directed object interaction tasks with a specific movement sequence requiring reach-grasp-transport-release object manipulations. The tasks in this study were modelled after activities of daily living, but were more controlled than Land or Hayhoe's tea and sandwich making tasks. In the Pasta Box Task, participants moved a pasta box between three targets on shelves of varying heights, and in the Cup Transfer Task, participants moved compliant cups filled with small beads (as a proxy for liquid) over a barrier and placed them on specific targets. Both tasks were designed to resemble activities one would usually perform in the kitchen, but were more constrained with targets for object placement and a specified order, to allow for automated segmenting and analysis of the data. This approach allowed Lavoie et al. to complete one of the most detailed assessments of eye gaze behaviour to date, as they were able to accurately analyze 800 trials (20 participants 2 tasks x 20 trials), while Land and Hayhoe's observations were based on 3 and 4 participants, respectively.

Key findings from Lavoie et al. (2018) were consistent with prior work, but provided a higher level of insight into behaviour throughout reach-grasp-transport-release manipulations. Participants would fixate their gaze on the task objects an average of 0.5 to 0.9 s before picking them up. Participants also spent an average of 73 to 80% of the time fixating on task-relevant objects, with the other 17 to 20% primarily taken up by blinks and saccades. Additionally, participants rarely fixated on their hand throughout the tasks. Due to the standardized sequence and object positioning in the tasks, Lavoie et al. were also able to gain precise information about behaviour during reach-grasp-transport-release object interactions. In addition to quantifying the eye-hand lead time before object pick-up, they found that able-bodied participants continued to fixate on objects being picked up throughout the grasp phases (of 0.2 seconds on average), and then tracked the moving object/their hand for up to 0.1 s after the initiation of transport, before transitioning their gaze to the object drop-off target and arriving there an average of 0.6 to 0.9 s before drop-off. Lavoie et al. also observed that the amount of body movement required to fixate on an area of interest influenced how much it was fixated. When participants had to turn their body to the side to pick up an object, able-bodied individuals did not fixate on it as much during reach compared to when they were picking up an object in front of them. This indicated that able-bodied individuals are capable of reducing the extent to which their gaze proceeds an action if it is not convenient to look ahead as early, and they have other information to guide their movement (such as proprioceptive feedback and knowledge of the standardized object placement).

In summary, across a variety of goal-directed tasks, eye gaze behaviour of able-bodied individuals has been characterized as preceding action by up to 1 s, focusing almost exclusively on task-related areas of interest, rarely fixating on the hands, and quickly transitioning away from objects once they have been securely acquired by the hands.

2.3.2 Eye Gaze Behaviour in Upper Limb Prosthesis Users

In the last decade, motivated by observations about the demand for visual attention when operating a prosthetic device, researchers have begun to apply head-mounted eye tracking to characterize the eye gaze behaviour of individuals who are using an UL prosthesis to complete object manipulation tasks. Compared with the documented behaviour of individuals using their anatomic hand, some notable differences have been observed.

Bouwsema et al. (2012) were the first group to use eye tracking to report on gaze behaviour in prosthesis users. In this study of five experienced transradial myoelectric prosthesis users, they identified two gaze behaviour strategies. During object grasping and manipulation (removing a Velcro cover), they observed that three of the prosthesis users primarily fixated on the object, while two individuals frequently switched their gaze between the object and their terminal device in order to monitor their hand more. The authors did not record the eye gaze behaviour of able-bodied individuals performing their task, but based on research discussed in the previous section, it can be assumed that able-bodied individuals would primarily fixate on the object, while the strategy of frequent gaze transitions represents a divergence from normative behaviour. By comparing the trends in eye gaze behaviour to scores from the Southampton Hand Assessment Procedure (SHAP) and self-reported frequency of prosthesis use, Bouwsema et al. concluded that the gaze switching behaviour was more associated with limited use of the prosthesis in daily life rather than functional ability.

The results of Bouwsema's study were supported by another study (Chadwell et al. 2016), which used a different object manipulation task (picking up, rotating and placing a cylinder). Chadwell et al. showed that between two transradial myoelectric users, the individual who used their device more during daily life was able to look ahead more during the task, while the other individual focused on their hand for a much greater percentage of the task. However, in their follow-up study, Chadwell et al. (2018) concluded that there was no significant correlation between in-lab performance measures (including gaze behaviour) and real-world prosthesis usage. To date, they have not provided further detailed results on the in-lab gaze behaviour of the 20 transradial myoelectric prosthesis users included in the study.

Sobuh et al. (2014) were the first group to collect eye gaze data for able-bodied individuals and prosthesis users performing the same task. They compared the behaviour of seven able-bodied individuals with four experienced transradial myoelectric prosthesis users during a carton-pouring task. While reaching for and grasping the carton, they observed that prosthesis users looked more at their hand and the grasp-related area of the carton, whereas able-bodied individuals looked more at the top (pouring) part of the carton.

Then, during the pouring phase of the task, they found that both groups mostly watched the liquid coming out of the carton, but the prosthesis users had an increased number of saccades during this time.

This study (Sobuh et al. 2014) also compared the eye gaze behaviour of four transradial myoelectric prosthesis users to the behaviour of seven able-bodied individuals using a simulated transradial myoelectric prosthesis. They found “reasonable agreement” between gaze behaviour of the actual and simulated prosthesis users, except with respect to number of gaze transitions during object manipulation (simulated prosthesis users had fewer gaze transitions). They attributed this to the level of familiarity of the simulated prosthesis users with the task, as they had been given two weeks of training sessions with the prosthesis simulator before the comparison was made, while the experienced prosthesis users did not practice the specific task beforehand. Sobuh et al. did not find a statistically significant effect on gaze behaviour of the simulated prosthesis users over the training sessions, but there was a trend towards fewer gaze transitions and less fixation to hand after training.

In 2017, Parr et al. undertook one of the largest studies characterizing eye gaze behaviour of simulated prosthesis users, with 21 able-bodied individuals using a simulated transradial myoelectric prosthesis. Parr used a coin drag-and-drop task, taken from the SHAP, and found that when participants were using the simulated prostheses, they focused more on their hand and took longer to shift gaze from their current area of interaction to the next target, compared to their performance on the same task with their anatomic hand. They also found that the amount of time by which participants’ eye gaze led their hand was predictive of overall task performance (as represented by task completion time). One limitation of this study was that they allowed for significantly less practice with the prosthesis simulator (only one full trial) than in Sobuh’s study, and Parr reported different eye gaze metrics from those that Sobuh had used in comparisons with experienced prosthesis users. Another limitation of this study was that, due to the time-consuming nature of eye tracking analysis, they reported analyzing only one third of the eye gaze data that they collected, greatly reducing their pool of data.

To date, only one study has examined the effects of additional sensory feedback on the gaze behaviour of individuals using a prosthetic device. Raveh et al. (2017) explored the effects of vibrotactile feedback on the performance and eye gaze behaviour of 43 able-bodied individuals using a transradial myoelectric prosthesis simulator. Raveh et al. employed a dual-task paradigm, in which participants simultaneously performed two distinct tasks one with the prosthesis simulator, and one with their anatomic limb. With the prosthesis simulator, participants performed simple functional tasks such as moving a key onto a shelf and spooning/stirring sugar into a glass. With their other (anatomic) hand, they used a keyboard to control a car in a computer game. Raveh et al. did not find that the addition of vibrotactile feedback had any significant effect on the participants' eye gaze behaviour (number of gaze transitions and percentage of time focusing on the computer screen) or their performance in the computer game or functional tasks. However, one could argue that the participants were not given sufficient practice time with the simulated prosthesis (only 15 minutes) to become proficient enough to use the vibrotactile feedback effectively. Furthermore, the dual-task paradigm used in this study sounds particularly challenging, and the authors did not present data on the eye gaze behaviour of able-bodied individuals using their anatomic limb to perform this task for comparison. It is possible that individuals who were not using a simulated prosthesis would still also switch their gaze between the computer screen and functional tasks as often as the participants in this study in order to accomplish this task.

In summary, studies have shown that the eye gaze behaviour of individuals using a myoelectric prosthetic device differs from that of able-bodied individuals (Bouwsema et al. 2012; Sobuh et al. 2014; Parr et al. 2017). Specifically, while using a prosthetic device, individuals appear to fixate more on their hand, either by switching their focus between upcoming targets and their terminal device (Bouwsema et al. 2012), or by waiting longer to transition their gaze from a current area of interaction to an upcoming target (Parr et al. 2017). In general, this behaviour has been attributed to the increased cognitive demand of operating a prosthetic device and the decreased sensory feedback available, and it has been hypothesized that cutting edge prosthesis technology with integrated sensory feedback may reduce these differences from normative behaviour. Overall, these results indicate that eye tracking is a promising tool for assessing the efficacy of UL prosthetic device technology. However, there are limitations in the work that has been done in this field. First, most of the studies with prosthesis users have had very small sample sizes (4 or 5 prosthesis users), and the studies with larger sample sizes have used a simulated prosthesis with able-bodied participants instead of experienced prosthesis users. Second, these studies have used a variety of different tasks and outcome measures instead of a standardized protocol, making it difficult to compare between studies or pool results. Third, to date, the only population that has been included in these studies is transradial myoelectric prosthesis users. It would be useful to characterize the eye gaze behaviour of individuals with different levels of amputation, or different devices, especially body-powered prosthesis users.

2.3.3 End Effector Movement in Able-Bodied Individuals

In the previous sections, we have seen that the coordination between visual attention and action is a key aspect of gaze behaviour during functional interactions with objects. Therefore, it is necessary to track hand movement when characterizing gaze behaviour; furthermore, the characteristics and quality of hand movement may add further insight when interpreting visual behaviour.

In able-bodied individuals, reaching movements have consistently been characterized as having straight or gently curved hand trajectories and bell-shaped velocity profiles with a single acceleration phase followed by a single deceleration phase (Morasso 1981; Abend et al. 1982; Gordon et al. 1994). This single velocity peak is sometimes referred to as a "movement unit." The exception that has been observed is when an obstacle is introduced; end effector velocity profiles become dual-peaked as individuals use two movement units to move in a curved path around the obstacle (Abend et al. 1982; Valevicius et al. 2018).

During reach-to-grasp movements, Jeannerod (1984) showed that able-bodied individuals gradually widen their grip aperture throughout the reaching movement, arriving at a maximum aperture roughly 70 to 80% through the movement. This peak grip aperture generally corresponded with the point of peak deceleration in the deceleration phase of the reaching movement unit (Jeannerod 1984).

Valevicius et al. (2018) added to the literature on natural hand movement by examining reach-to-grasp movements with a goal-directed completion of object manipulation (reach-to-grasp followed by a transport-release phase) during the same protocol for the Pasta Box and Cup Transfer Tasks previously mentioned in section 2.3.1 (Lavoie et al. 2018). They found that transport movements exhibited similar velocity profiles as reaching movements (bell shaped profiles with a single peak, or dual-peaked profiles if the individual was required to clear an obstacle during the transport). Valevicius et al. also introduced additional variability in task demands with lateral reaches, barriers to be cleared, and more risky object interactions in the form of compliant cups with contents that could be spilled. This allowed the identification of some circumstances where coupling of peak grip aperture and peak hand deceleration did not occur. Able-bodied individuals reached peak hand deceleration prior to peak grip aperture during lateral reaches to pick up an object originally at their side, and when reaching to pick-up the compliant cups with contents that could be spilled. This is in contrast to prior literature in which coupling of hand deceleration and peak grip aperture was observed (Jeannerod 1984), and demonstrates the importance of including tasks with more real-world demands in order to fully assess visuomotor behaviour.

2.3.4 End Effector Movement in Upper Limb Prosthesis Users

Relative to able-bodied individuals, the end effector movements of upper limb prosthesis users during reaching and grasping have generally been characterized as slower with less smooth trajectories, as evidenced by an increase in sub-movements.

In 1981, Fraser and Wing compared the reaching and grasping behaviour of an individual using a transradial body-powered prosthesis with the same individual using their other (intact) limb (Fraser & Wing 1981). They found that this individual's reaching movement was slower when using their prosthesis, and that their grip aperture profiles would show a plateau at the maximum grip aperture, as opposed to a peak (which was observed when using their intact limb). Fraser and Wing also noted that when using their prosthesis, this individual would make a number of small movement adjustments as they approached an object to pick it up.

Bouwsema et al. (2010) characterized the movement patterns of three transradial myoelectric prosthesis users and three transhumeral hybrid (myoelectric hand and body-powered elbow) prosthesis users. Despite the differences in types of prostheses, Bouwsema et al. made similar observations to Fraser and Wing. The myoelectric and hybrid prosthesis users all demonstrated long movement times, a plateau in grip aperture and less smooth movement trajectories as evidences by multiple peaks in the velocity profiles (this was especially true for the transhumeral hybrid prosthesis users). Bouwsema et al. speculated that prosthesis users might move more slowly because they rely on visual feedback which is processed more slowly than proprioception. It was also noted in this study that the myoelectric and hybrid prosthesis users did not begin opening their hand until they were several hundred milliseconds into the reach movements, which they referred to as an "uncoupling of reach and grasp."

In recent years, upper limb prostheses have become more dexterous and included control of more degrees of freedom. Cowley et al. (2016) compared the movement quality of individuals using a new prosthesis with active wrist control (the DEKA arm) with the same individuals using their conventional prosthesis (two myoelectric and one body-powered prosthesis) as well as ten able-bodied individuals. Compared with able-bodied individuals, the prosthesis users consistently demonstrated slower movement times, lower peak hand velocities and more sub-movements during grasp when using both their conventional prostheses and the DEKA arm. For two of the prosthesis users, their movement quality decreased when using the DEKA arm, while the third individual's movement quality increased.

In summary, upper limb prosthesis users with both body-powered and myoelectric devices have been shown to move more slowly and with less smooth end effector trajectories than able-bodied individuals. It has been speculated that the decreased movement speed of upper limb prosthesis users is related to their increased reliance on visual feedback (Bouwsema et al. 2010). However, while it has been shown that prosthesis users (specifically myoelectric users) dedicate more visual attention to their terminal device (see section 2.3.2), whether this is the cause of their decreased speed is unclear.

Chapter 3. Methods

3.1 Participants

Five individuals with a transradial (TR) upper limb amputation and three individuals with a transhumeral (TH) upper limb amputation participated in this study. All of the participants regularly use a body-powered prosthesis with a voluntary opening split hook terminal device. Additional characteristics of the participants are summarized in Table 3.1, along with their scores on two standard clinical outcome measures, the Activities Measures for Upper Limb Amputees (AM-ULA) (Resnik et al. 2013), and a self-reported survey, the Upper Extremity Functional Status (UEFS) section of the Orthotics Prosthetics Users Survey (OPUS). The AM-ULA is a performance-based measure in which participants are asked to complete 18 activities of daily living (e.g. using utensils, combing hair, etc.) and then scored by a trained rater based on factors such as the extent to which they are able to complete the tasks, speed of completion and quality of movement. Scores for each task range from one to four, the summary score presented in Table 3.1 represents the average score across tasks multiplied by 10 (maximum score = 40) (Resnik et al. 2013). The AM-ULA was administered by and scored by a certified Occupational Therapist. The UEFS is a self-rated measure of an individual's assessment of their own upper limb functional ability based on 23 activities (e.g. wash face, use utensils, etc.). A higher score indicates a greater level of self-reported functionality (maximum score = 92).

Table 3.1: Summary of prosthesis user participants ordered from highest to lowest level of functionality with their prosthesis, based on scores from the AM-ULA.

Level of Amputation	Transradial					Transhumeral		
Participant ID	P66	P14	P85	P50	P94	P44	P96	P03
Gender	M	M	M	M	M	M	M	F
Age (years)	59	55	45	64	31	37	38	54
Amputation side	Right	Left	Right	Both[1]	Right	Left	Left	Left
Years since amputation at date of testing	28	26	10	12	5	8	10	1
Hours per day of prosthesis use	12	8	12	14	–[2]	14	12	2
AM-ULA	26.1	21.7	20	17.8	16.7	16.7	–[3]	12.2
UEFS	67.8	70.2	59.1	49.7	76.7	76.4	62.6	56.8

[1] Completed experimental tasks with right arm
[2] Not recorded
[3] Not assessed, but assumed to be more functional with prosthesis than P03 based on higher UEFS score and longer period of time since amputation

Inclusion criteria for this study were individuals with an upper limb amputation between the ages of 18 and 70 who were able to use their prosthesis to grasp and move objects, and had sufficient comprehension of the English language and cognition to provide informed consent in English. Participants were not included in the study if they were not willing or able to comply with the testing protocol, not able to wear their prosthesis for two continuous hours, experienced pain or discomfort when using their prosthesis, or had low back pain (self-rated as continuously exceeding 3 on a scale from 0 to 10 on the day of testing). The study followed the Declaration of Helsinki guidelines and was approved by the University of Alberta Health Research Ethics Board (Pro00054011), the Department of the Navy Human Research Protection Program (DON-HRPP), and the SSC-Pacific Human Research Protection Office (SSCPAC HRPO), and all participants provided voluntary written informed consent.

3.2 Experimental Protocol

3.2.1 Functional Tasks

Participants in this study were asked to complete two functional tasks: a Cup Transfer Task and a Pasta Box Task (Valevicius et al. 2018; Lavoie et al. 2018) while motion and eye tracking data was collected. The set-up for the motion capture and eye tracking systems is described in sections 3.2.2 and 3.2.3 respectively. Both tasks were completed while standing in front of a cart at a standard counter height of 36 in. Participants were asked to perform the tasks using only their prosthesis, with their other arm kept in a relaxed position by their side or resting on the cart in front of them. Before data collection, participants were shown a demonstration of the tasks and given an opportunity to practice both tasks. Based on this practice, the task that they were more confident with was selected as the first task to perform. Task order was determined this way instead of randomization, in an effort to prevent participants from becoming discouraged early on, as the tasks were specifically designed to be challenging for prosthesis users. Four of the five individuals with a transradial amputation started with the Pasta Box Task (therefore identifying this as the easier task), while only one of the three individuals with a transhumeral amputation found the Pasta Box Task easier than the Cup Transfer Task.

Immediately before data was collected for each task, instructions for the task were reviewed, and the participant was given more time to practice until they were comfortable with their strategy for achieving the task. Participants completed up to eleven trials of each task, and were instructed to complete each trial quickly but accurately. If they made an error during task execution (e.g., dropping an object, performing the task movements in an incorrect order), participants were asked to complete the trial to the best of their ability. Error trials were not used in data analysis, but participants were not asked to complete extra trials to make up for error trials.

The Cup Transfer Task and Pasta Box Task are summarized below. For complete task protocols, see Valevicius et al. 2018.

3.2.1.1 Cup Transfer Task

In the Cup Transfer Task, participants move two compliant cups filled with therapeutic beads from one side of a box, over a partition, and back again (Figure 3.1). The task set-up includes specific targets on which the cups must be placed on both sides of the box. Both cups start on the same side of the body as the arm that will be used to perform the task (the side of the prosthesis in this study). The task consists of four movements:

1) Move the cup that is nearest to the body (Green cup) over the partition and place it on its target
2) Move the cup that is farthest from the body (Blue cup) over the partition to its target
3) Move the far (Blue) cup back to its starting position
4) Move the near (Green) cup back to its starting position

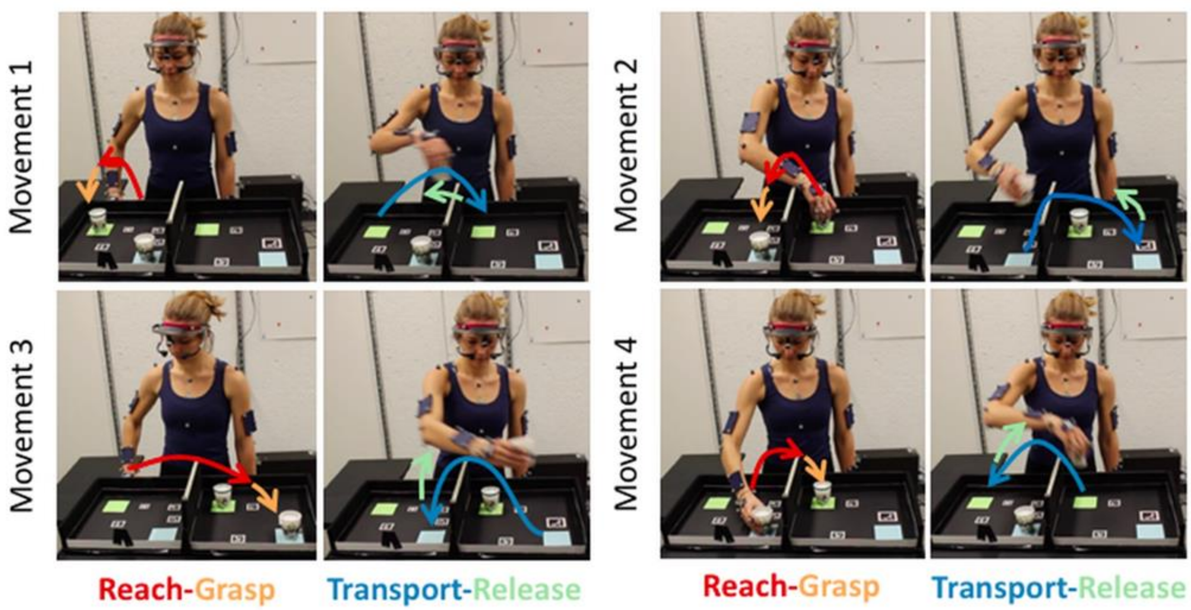

Figure 3.1: Movement sequence of the Cup Transfer Task. (Valevicius et al. 2018. Available under a Creative Commons Attribution Licence.)

The participant is asked to start and end the task looking at a neutral location (on the far side of the box partition) that is marked with a reflective motion capture marker, and with their end effector touching a 'home' target that is on the same side of the body as their task arm (prosthesis side). In between movements 2 and 3, the participant is asked to touch the home target again, but they do not have to look at the neutral marker at this time.

For individuals who are completing the task with their anatomic hand, or using a hand-shaped terminal device, the near (Green) cup is to be grasped with a top grasp and the far cup is to be grasped with a side grasp. However, these grasp patterns were not enforced with individuals who were using a split-hook terminal device, as it would have made the task prohibitively difficult.

3.2.1.2 Pasta Box Task

In the Pasta Box Task, participants move a box of pasta between three targets at varying heights (Figure 3.2). The pasta box starts on a 30 in high table at the side of the participant, on the same side of their body as the arm that will be used to perform the task (the side of amputation in this study). Two shelves are added to the cart in front of the participant (which is 36 in high): one 7 in above the cart, on the same side of the body as their task arm (amputation side); and one 12 in above the cart on the opposite side of the body as their task arm. The task consists of three movements:

1) Move the pasta box from the side table to the first (7 in high) shelf
2) Move the pasta box from the first shelf to the second (12 in high) shelf, around a barrier between the two shelves
3) Move the pasta box from the second shelf back to its starting position on the side table

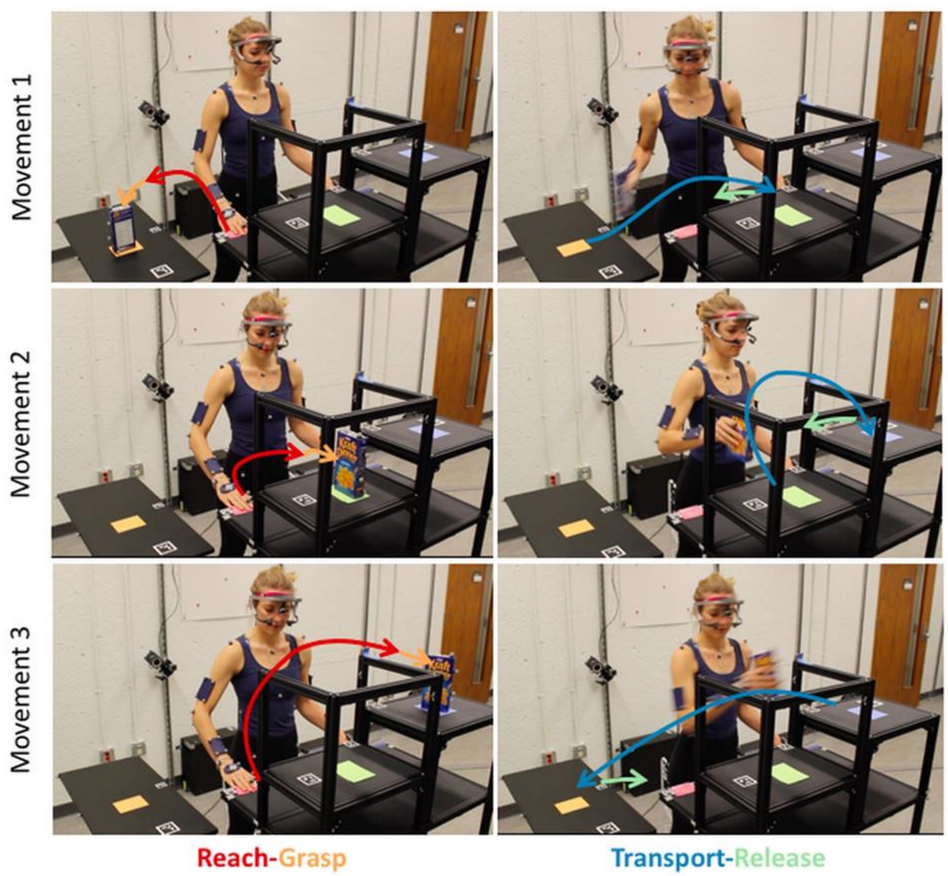

Figure 3.2: Movement sequence of the Pasta Box Task. (Valevicius et al. 2018. Available under a Creative Commons Attribution Licence.)

The participant is asked to start and end the task looking at a neutral location (in between and above the two shelves) that is marked with a reflective motion capture marker, and with their end effector touching a ‘home’ target that is on the same side of the body as their task arm (amputation side). The participant is also asked to touch the home target in between each movement, but they do not have to look at the neutral marker at these points in time.

3.2.2 Motion Capture Set-Up

A 12-camera Vicon Bonita motion capture system (Vicon Motion Systems Ltd, Oxford, UK) was used to track movement of reflective markers affixed to the participant’s terminal device and head, as well as other task relevant objects.

Reflective motion capture markers were fixed to all objects which were relevant to completion of the experimental task, including the cart on which the tasks were performed, and objects that would be manipulated during the tasks. A minimum of three markers (14 mm in diameter) were placed on each rigid body, except in the case of the cups used in the Cup Transfer Task, which were each tracked using only one marker (11 mm).

A rigid cluster with three reflective markers was fixed to the dorsal side of the participant’s prosthetic terminal device using double-sided tape (Figure 3.3). Each marker on this cluster was 11 mm in diameter, and the entire cluster was 65 mm in its longest direction. The experimenters endeavored to attach the cluster to a fixed point that would not move or rotate when the hook was opened. In addition to the marker cluster, two individual reflective markers (11 mm) were fixed to each side of the split hook (Figure 3.3) to track grip aperture, and four markers were attached to a headband to track movement of the head. The Vicon motion capture system tracked the 3D trajectory of each reflective marker at a sampling rate of 120 Hz, with an accuracy of 0.5 mm. Marker clusters were also attached to the other segments of the upper body kinematic chain (forearm, upper arm, trunk, pelvis), but these were not used in the current analysis. A complete list of motion tracking markers used in this analysis is provided in Table 3.2.

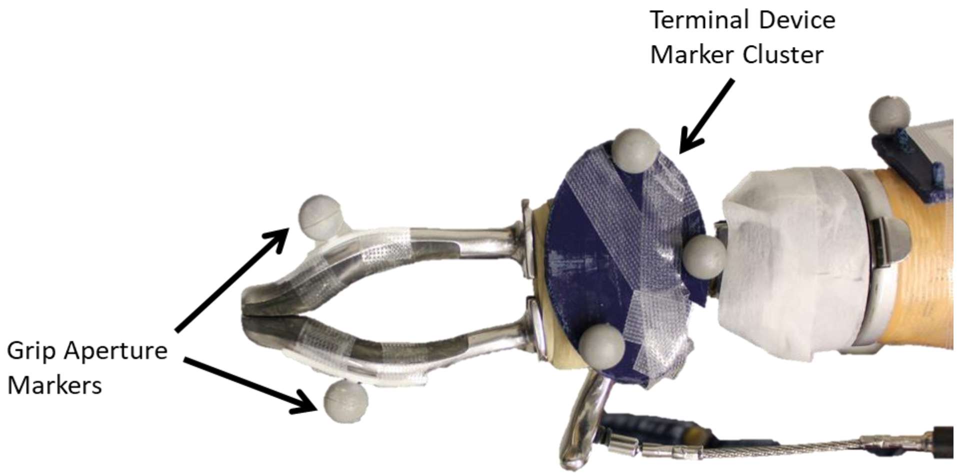

Figure 3.3: Placement of motion capture marker cluster tracking participant's terminal device, and individual markers tracking grip aperture of participant's split hook.

Table 3.2: Locations of motion capture markers used in current analysis.

	Entity Being Tracked	# of Markers	Marker Location(s)
Rigid Bodies	Task Cart	4	Two markers along the back edge of the cart. One on the front edge, on the opposite corner to the task arm. One in the middle of the side edge, on the same side as the task arm (Figure 3.4a).
	Side Table	4	See Figure 3.4a.
	Participant's Terminal Device	3	Custom 3D printed marker cluster. Attached to point on terminal device that will not translate or rotate when hook is opened (Figure 3.3).
	Participant's Head	4	Two markers placed symmetrically on forehead, two markers placed asymmetrically on back of head.
	Pasta Box (Pasta Box Task – section 3.2.1.2)	4	Three markers on narrow side of pasta box, opposite to side participant will be grasping. One on wide side, at the bottom (Figure 3.4b).
	Wand (Gaze Calibrations – section 3.2.4)	4	One marker on tip of wand, three more for improved tracking of wand (Figure 3.6).
Individual Markers	Participant's Split Hook	2	One marker attached to each side of the participant's split hook terminal device (Figure 3.3).
	Cups (Cup Transfer Task – section 3.2.1.1)	2	One marker attached to the side of the Near (Green) Cup using double sided tape. One attached to the rim of the Far (Blue) Cup using a custom 3D printed component.
	Neutral Eye Gaze Target	1	One marker attached to a neutral gaze location

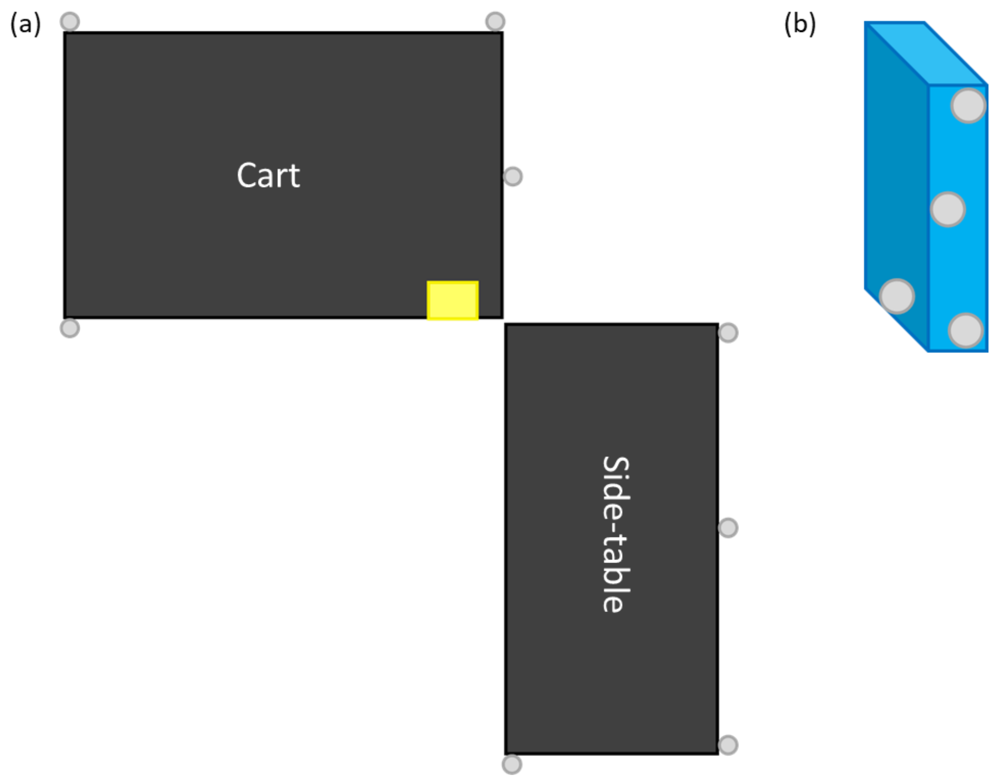

Figure 3.4: Placement of reflective motion capture markers on: (a) the cart and side-table– top-down view, where participant would be facing bottom edge; and (b) the pasta box – 3D view, where participant would be grasping the far (non-markered) side. Marker placement is shown for right-handed task set-up. For a left-handed set-up the cart and side-table would be mirrored.

3.2.3 Eye Tracking Set-Up

A binocular head-mounted eye-tracker (Dikablis Professional 2.0, Ergoneers GmbH, Manching, Germany) was used to track participants' eye gaze behaviour. The eye-tracker, shown in Figure 3.5, rests on the wearer's nose and sides of their head (above the ears) like a pair of glasses, and also has a forehead contact and strap to hold it securely on the wearer's head. It includes two cameras which are directed at the wearer's eyes (pupil cameras) and can be adjusted to optimally capture their eye movements. The eye-tracker illuminates the eyes with near-infrared light, and the infrared-sensing pupil cameras record the patterns of reflection at a sampling frequency of 60 Hz. The eye tracker is connected to a desktop computer via a 5 m long USB cable which gave the participants enough slack to move freely while wearing it. The eye-tracker also included a forward facing (scene) camera that would be used in traditional eye-tracking analysis to correlate pupil position with the wearer's point of regard relative to the scene in front of them. However, only the pupil data was used in the present analysis (see section 3.3).

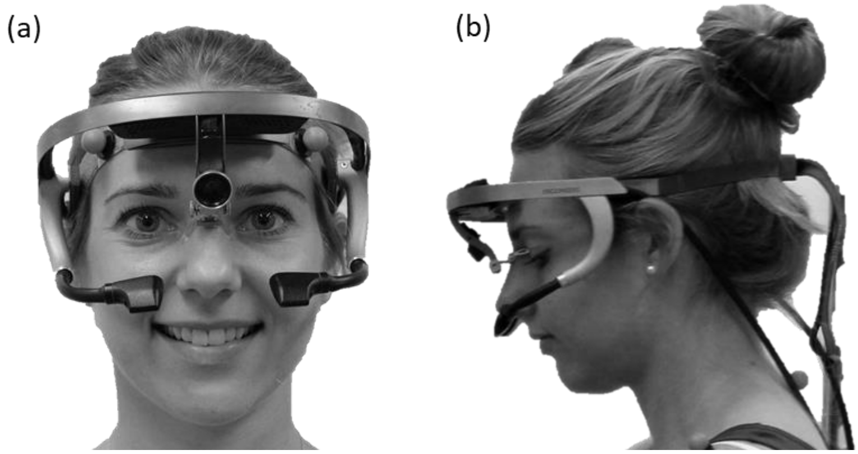

Figure 3.5: Dikablis Professional 2.0 Eye Tracker from (a) the front, and (b) the side. The individual in the figure has provided written consent to publish the photographs.

3.2.4 Gaze Calibration

In order to integrate the eye and motion tracking data, a calibration routine was performed after the eye-tracker and motion capture marker set-up had been completed, but before the functional task trials. The participant was asked to stand in the motion capture volume where they would be completing the experimental tasks, and keep their gaze fixated on a motion capture marker attached to the tip of a wand (Figure 3.6), as it was moved around the task area by an experimenter. The wand was moved in large, S-shaped, sweeping movements that encompassed the task area, and then to specific task relevant areas as shown in Figure 3.7. Three sweeping movements were completed: right-to-left, in a plane parallel to the participant's coronal plane but above the task cart; up-and-down, also in a plane parallel to the participant's coronal plane but above the cart; and front-to-back along the depth of the cart. After the three sweeping movements were completed, the wand was moved to the approximate locations of the task-relevant areas of interest for both the Cup Transfer Task and Pasta Box Task (all object targets). The wand was moved to the 'home' target between each section of the gaze calibration routine (Figure 3.7). A new calibration routine was completed before each set of task trials (one per task).

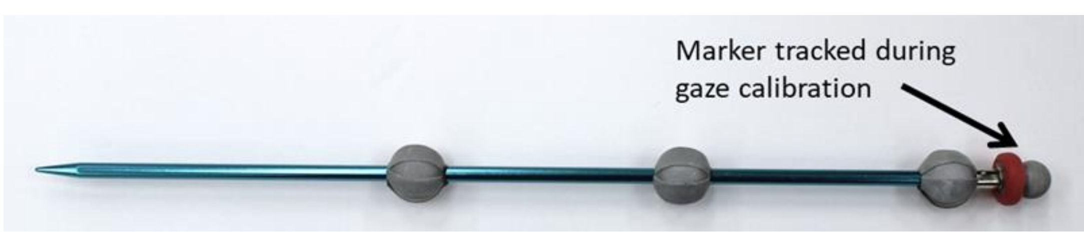

Figure 3.6: Gaze calibration wand.

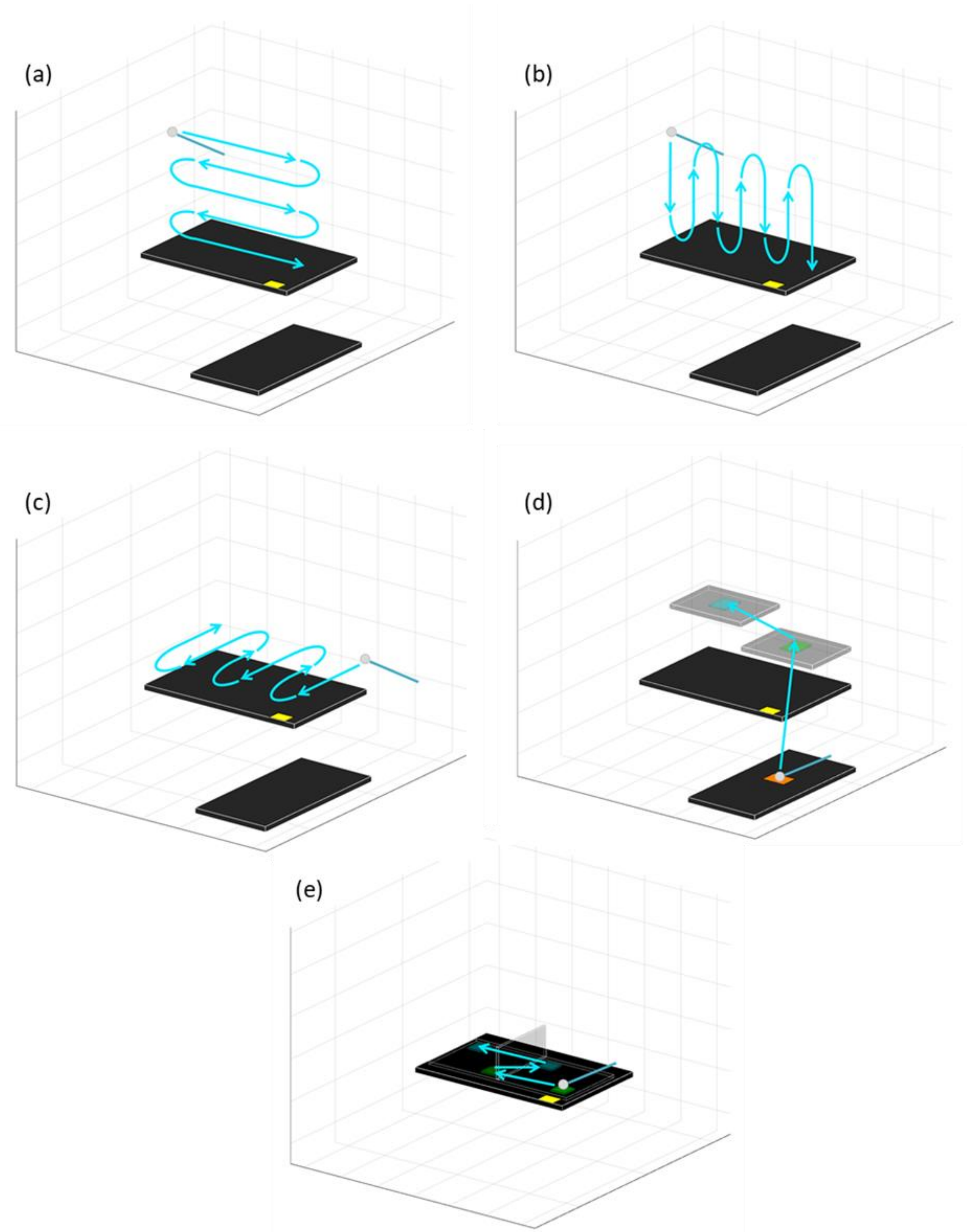

Figure 3.7: Gaze calibration routine: (a) right-to-left wand movements; (b) up-and-down wand movements; (c) front-to-back wand movements; (d) Pasta Box Task areas of interest; (e) Cup Transfer Task areas of interest. The gaze calibration wand is also moved to the 'home' target (identified with the yellow rectangle) between each section (a-e) of the calibration routine.

3.3 Data Processing

3.3.1 Cleaning and Exporting Raw Motion Capture Data

After data collection, tools available in Vicon's motion tracking software (Nexus v2.3, Vicon Motion Systems Ltd, Oxford, UK) were used to fill gaps in marker trajectories and correct instances of marker switching. Cleaned, 3D marker trajectory data for each tracked marker were then exported to a comma-separated values (CSV) file. One CSV file was generated for each gaze calibration and task trial performed. After the marker data were exported, the motion capture marker trajectories were filtered in MATLAB (MathWorks, Natick, MA, US) using a 2^{nd} order bidirectional low-pass Butterworth filter (resulting in a 4^{th} order zero-lag filter) with a cutoff frequency of 6 Hz (Winter 2009; Delextrat & Goss-Sampson 2010).

3.3.2 Exporting and Cleaning Raw Eye Tracking Data

Video from the eye-tracker pupil cameras was processed using proprietary software (D-LAB 3.0, Ergoneers GmbH, Manching, Germany), which used image processing algorithms to estimate the position of each pupil centre at every frame of the pupil camera video. These pupil coordinates were then exported as text files, with one file per gaze calibration or task trial. The exported pupil coordinate data were subsequently cleaned using an automatic cleaning script written in MATLAB. The objective of the cleaning script was to identify and remove incorrect data points, which can occur in eye tracking when the algorithm detects the wearer's eyelashes or a dark part of their iris instead of the pupil, as well as filter the data and fill in small gaps. The algorithm employed by the cleaning script is outlined in Appendix A.

3.3.3 Synchronization of Motion and Eye Tracking Data

During data collection, a custom software program was used to simultaneously trigger the start and end of motion capture and eye-tracking data recording for each trial. In post-processing, the motion and eye tracking data for each trial was aligned using a custom MATLAB script that assumed simultaneous end times for the exported data files. The eye-tracking data were then interpolated to match the sampling frequency of the motion capture system (60 Hz to 120 Hz), and the aligned data sets were saved in new CSV files containing combined motion and eye tracking data.

3.3.4 Technical Development and Data Analysis in GaMA

In order to perform integrated analysis of the aligned motion and eye tracking data, a custom software program: Gaze and Movement Analysis (GaMA) was created using MATLAB. GaMA accepts, as input, combined files containing synchronized motion and eye tracking data (section 3.3.3), and displays this data in a graphical user interface (GUI) as shown in Figure 3.8. The GUI contains two 2D 'Pupil Coordinate Displays' for visualizing the raw eye-tracking data from each pupil camera; as well as a 3D 'World Viewer', which displays the 3D motion capture marker coordinates and will also be used to visualize additional data which will be created using the software. GaMA includes a number of tools which allow the user to add layers of data to the original marker and pupil data. The following sections outline the data processing steps that were performed in GaMA for the current analysis. GaMA was developed with batch processing capabilities, so that, for each processing step, the user is only required to define relevant variables once for each task, and then the analysis could be automatically applied to sets of trials with the same set-up.

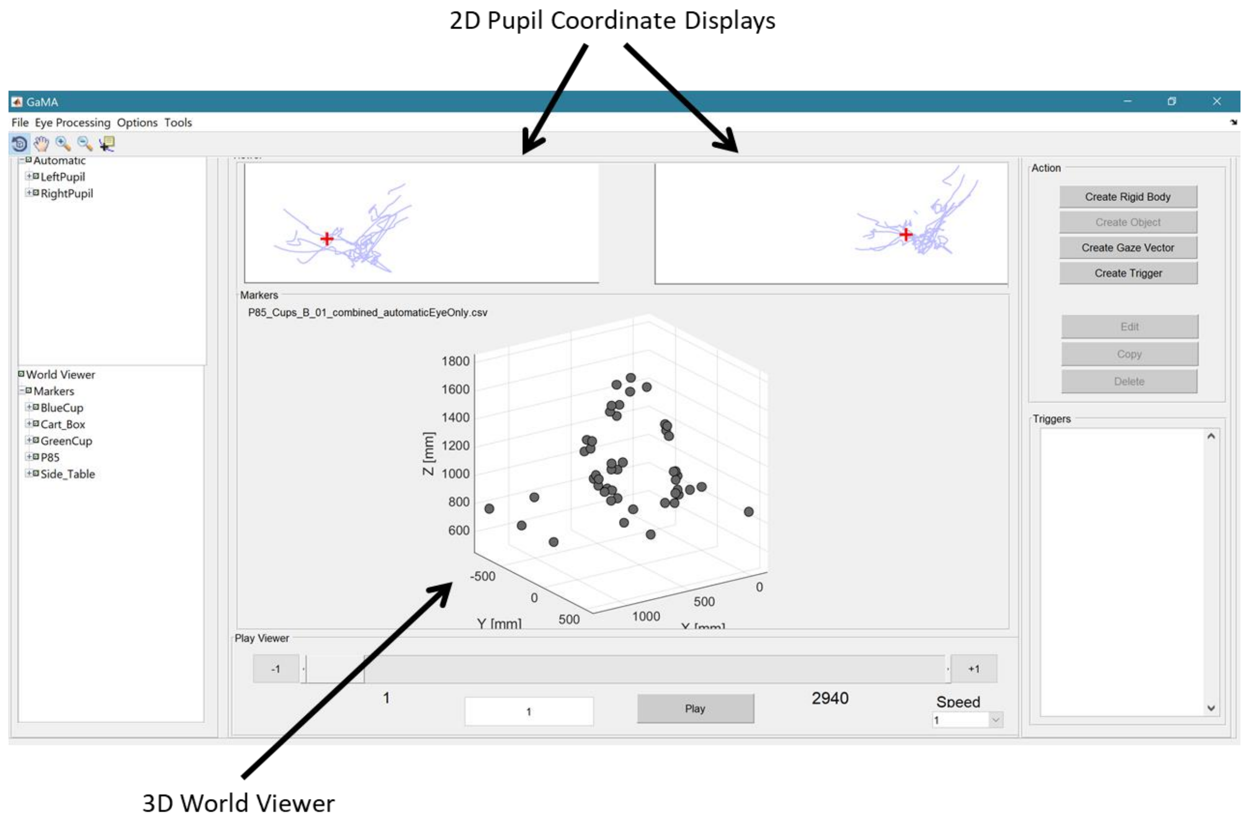

Figure 3.8: Graphical User Interface for the GaMA software; including pupil coordinate displays for visualization of raw data from the eye tracker, and world viewer for visualization of raw motion capture data (3D marker positions) as well as additional data created using the software tool.

3.3.4.1 Rigid Bodies and Objects

The GaMA software allows the user to identify sets of markers that were attached to the same rigid body and add virtual objects to these sets of markers. These tools allow the user to create a virtual representation of the 3D environment in which an individual was acting, as well as a representation of the individual themselves. The properties of this virtual world, such as the distances between objects and speeds at which they are moving will be used for further analysis.

Rigid Bodies are identified in GaMA using sets of three motion capture markers attached to the task-relevant rigid bodies (Table 3.2). GaMA uses the 3D marker trajectories for the set of markers to calculate the position and orientation (stored as XYZ moving axes Euler Angles) of each rigid body at each frame of a trial. This calculation was done for each rigid body listed in Table 3.2 (section 3.2.2). Creating virtual objects then allows the user to assign extent to these rigid bodies and create a full virtual representation of the space occupied by each task-relevant entity. When a virtual object is created in GaMA, it is visualized in the World Viewer (see example in Figure 3.9) and data representing the coordinates of each of its vertices is added to the raw motion and eye-tracking data, so it can be used in subsequent calculations. GaMA allows the user to visualize objects as rectangular prisms, cylinders or spheres, but this is only for visualization purposes; internally, all objects are treated as rectangular prisms.

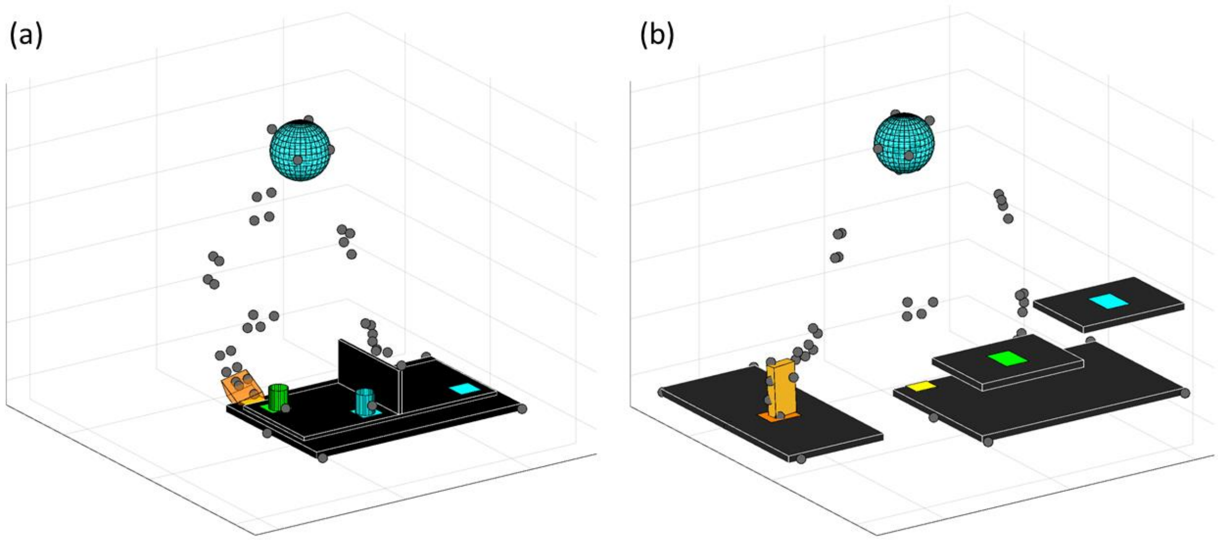

Figure 3.9: GaMA World Viewer with virtual objects added for (a) the Cup Transfer Task, and (b) the Pasta Box Task.

Multiple virtual objects can be added to the same rigid body. For example, in the Pasta Box Task, the cart was tracked using four motion capture markers (section 3.2.2) which were identified as a rigid body in GaMA. A virtual object representing the cart was then added to this rigid body, as well as objects representing the home target, shelves and pasta box targets on each shelf, because these objects were permanently positioned relative to the cart.

Screenshots of the GaMA World Viewer showing all objects created for the Cup Transfer and Pasta Box Task environments are provided in Figure 3.9. In addition, a complete list of the virtual objects which were created in GaMA for each task is provided in Table 3.3.

In the current analysis, there were two objects which had to be added to single markers instead of rigid bodies: the cups in the Cup Transfer Task. Since the cups were not large enough to support a rigid cluster of at least 3 markers without affecting the participants' interaction with them, individual markers were used to track the movement of the cups (section 3.2.2). The consequence of this is that the virtual cup objects created in GaMA must assume that the cups are always held vertically and, thus, can only represent the approximate position of the cups, but not capture their orientation.

Table 3.3: List of virtual objects created using the GaMA software tool for the Cup Transfer Task and Pasta Box Task.

Task	Parent Entity	Object
Cup Transfer Task	Cart Rigid Body	Cart Object Home Target Cup Box Base Cup Box Partition Near (Green) Cup Starting Target Near (Green) Cup Second Target Far (Blue) Cup Starting Target Far (Blue) Cup Second Target
	Near (Green) Cup Marker	Near (Green) Cup Object
	Far (Blue) Cup Marker	Far (Blue) Cup Object
	Participant's Terminal Device Rigid Body	Participant's Terminal Device Object
	Participant's Head Rigid Body	Participant's Head Object
Pasta Box Task	Cart Rigid Body	Cart Object Home Target Shelf 1 Pasta Box Target on Shelf 1 Shelf 2 Pasta Box Target on Shelf 2
	Side Table Rigid Body	Side Table Object Pasta Box Target on Side Table
	`	Pasta Box Object
	Participant's Terminal Device Rigid Body	Participant's Terminal Device Object
	Participant's Head Rigid Body	Participant's Head Object

3.3.4.2 Task Segmentation

Task trials were segmented in GaMA based on a combination of terminal device velocity, object velocities, and distances between different objects in the environment (including the participant's terminal device) (Valevicius et al. 2018). The tasks were segmented based on the movements outlined in sections 3.2.1.1 and 3.2.1.2 (4 movements in the Cup Transfer Task and 3 Movements in the Pasta Box Task). Each movement sequence was further segmented into Reach, Grasp, Transport, and Release phases, based on criteria which are summarized in Table 3.4.

Table 3.4: Criteria used to define Reach, Grasp, Transport and Release phases for segmentation of task trials in GaMA. Adapted from Valevicius et al. 2018.

Phase	Start/End	Definition
Reach	**Start**: Hand leaves the home position OR end of previous Release phase	(When hand is leaving home) Earlier of the following two events: 1. First occurrence of the hand velocity exceeding the `Hand Velocity Threshold' (see below) 2. First occurrence of the hand moving more than 7 cm from its start position
Grasp	**Start**: Closing of grip aperture	*Find hand centroid position at Transport start First occurrence of the hand distance from its Transport start position falling below the relevant `Grasp Distance Threshold'
Transport	**Start**: Start of object movement	Earlier of the following two events: 1. First occurrence of the object velocity exceeding the `Object Velocity Threshold' (see below) 2. First occurrence of the object moving more than 7 cm from its start position
Release	**Start**: End of object movement	Later of the following two events: 1. First occurrence of the object velocity falling below the `Object Velocity Threshold' 2. First occurrence of the object moving within 7 cm of its drop-off target
	End: End of grip aperture opening	*Find hand centroid position at Transport end Last frame before first occurrence of the hand distance from its Transport end position exceeding the relevant `Release Distance Threshold'

The phase definitions are based on hand and object positions and velocities which were calculated using the centroid of the virtual objects created for those entities. The 'Hand Velocity Threshold' is defined as 5% of the peak hand velocity during the currently analyzed trial. Similarly, the 'Object Velocity Threshold' is defined as 5% of the peak velocity for the relevant object during the trial. The 'Grasp Distance Threshold' and 'Release Distance Threshold' were defined based on data from 20 able-bodied individuals (Lavoie et al. 2018). They were calculated by finding the point of peak grip aperture before Transport start and after Transport end for every object manipulation, then determining the distance of the hand at peak grip aperture relative to its position at Transport start and end, and finally averaging these distances across trials and participants. Grasp and Release distance thresholds were not averaged across movements, however. Each movement in each task has a unique 'Grasp Distance Threshold' and 'Release Distance Threshold,' as summarized in Table 3.5.

Table 3.5: Grasp and Release distance thresholds used during segmentation of the Cup Transfer Task and Pasta Box Task trials in GaMA. (Adapted from Lavoie et al. 2018)

Task	Movement	Phase	Threshold Distance (cm)
Cup Transfer Task	1	Grasp	1.39
		Release	1.47
	2	Grasp	2.70
		Release	2.79
	3	Grasp	2.77
		Release	1.84
	4	Grasp	2.04
		Release	1.32
Pasta Box Task	1	Grasp	4.43
		Release	1.63
	2	Grasp	2.55
		Release	2.12
	3	Grasp	2.40
		Release	1.63

Data for each phase or each movement were stored as logical arrays (columns of zeroes and ones) the same length as the original data file, with ones indicating frames that were part of a given movement phase (e.g. movement one, Reach phase), and zeros otherwise.

3.3.4.3 Gaze Vector

The Gaze Vector is the tool that allowed GaMA to integrate the eye-tracking and motion capture data. In this processing step, the gaze calibration (section 3.2.4) is used to predict the 3D eye gaze fixation point of the participant in the motion capture coordinate system, for each related task trial. Two things are required to make this prediction:

1) A task trial with synchronized eye and motion tracking data, in which the rigid body tracking the participant's head has been identified (section 3.3.4.1)
2) A corresponding gaze calibration file with synchronized eye and motion tracking data in which:
    a. The eye-tracking and motion capture marker set-up is identical to the task trial (i.e. eye tracker has not been bumped or adjusted, head markers have not been moved)
    b. The participant's gaze is constantly fixated on a single marker that is tracked by the motion capture system as it is moved around the task space (section 3.2.4)

The following algorithm is applied to predict the participant's eye gaze fixation point throughout a given task trial:

1) In the gaze calibration data set, transform the coordinates of the fixated marker from the global motion capture coordinate system, into the coordinate system of the head rigid body
2) Create three linear models relating the pupil coordinate data (X,Y coordinates for each eye) from the gaze calibration to the transformed fixation point coordinates (one model for each coordinate: X,Y,Z, relative to the head rigid body coordinate system)
3) Apply the models created in step 2 to the pupil coordinate data in the currently analyzed task trial to predict the eye gaze fixation point throughout the task, in the coordinate system of the head rigid body
4) Transform the predicted fixation point into the global motion capture coordinate system

The predicted fixation point is used to generate a vector originating at the participant's forehead (centre of the two forehead motion capture markers) and passing through the fixation point, as shown in Figure 3.10.

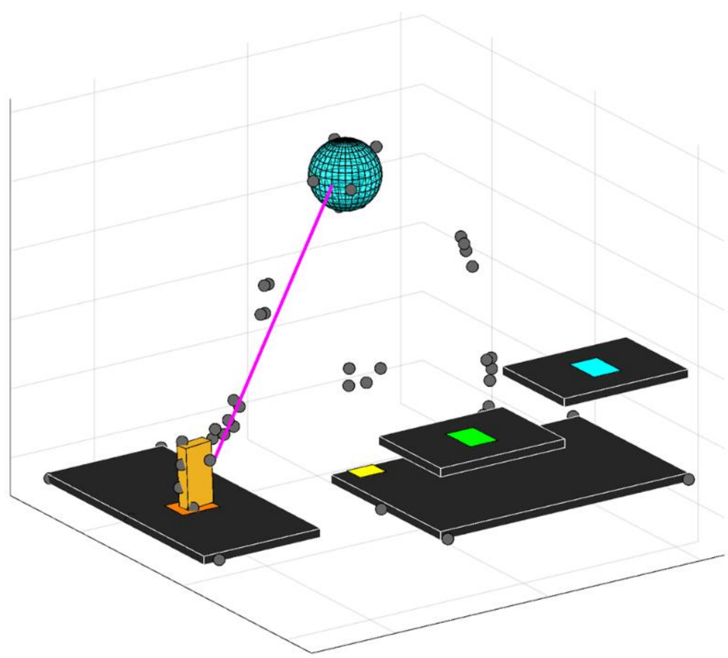

Figure 3.10: GaMA World Viewer displaying virtual objects for the Pasta Box Task and a gaze vector; representing participant's predicted gaze direction in 3D space, based on pupil coordinate and gaze calibration data.

The vector represents the participant's gaze direction throughout the trial, and in subsequent calculations is treated as infinite, because the predicted fixation point was observed to have low accuracy in the depth direction.

3.3.4.4 Fixation Detection

With the participant's gaze direction integrated into the 3D space of the motion capture data, rules were defined to automatically detect when the participant was looking at different objects throughout the task. For the purposes of this analysis, eye gaze fixation was defined as any period of time when:

> The participant's gaze was *stable* AND the gaze vector was intersecting a task relevant object or was below a tolerable distance threshold (Table 3.6) relative to an object.

Where gaze is considered to be stable if either of the following two conditions are met:

1. Pupil and head are stable - the velocity of the right pupil (in the 2D pupil camera coordinate system) is less than 30% of the pupil camera range per second AND the 3D velocity of the motion capture marker on the right side of the participant's forehead is less than 300 mm/s
2. Pupil is moving, and gaze is directed at a moving object - The gaze vector passes within 10 cm of any of the task relevant objects AND the relative velocity between the gaze vector and said object is less than 500 mm/s

Gaps in gaze stability that were shorter than 100 ms were filled in (the eyes were still considered to be stable during short gaps in stability), and periods where gaze stability was detected that were less than 100 ms long were deleted (eyes thought to be "flying through" relevant areas).

Table 3.6: Distance tolerances used for eye gaze fixation detection on task-relevant objects in the Cup Transfer Task and Pasta Box Task.

Task	Object	Distance Tolerance (cm)
Cup Transfer Task	Participant's Terminal Device	0
	Neutral Eye Gaze Target	2.5
	Home Target	1.0
	Near (Green) Cup	3.0
	Green Cup Target 1	3.0
	Green Cup Target 2	5.0
	Far (Blue) Cup	5.0
	Blue Cup Target 1	7.5
	Blue Cup Target 2	7.5
Pasta Box Task	Participant's Terminal Device	0
	Neutral Eye Gaze Target	2.5
	Home Target	5.0
	Pasta Box	5.0
	Side Table Target	10.0
	Shelf 1 Target	10.0
	Shelf 2 Target	22.5

The distance tolerances for fixation detection varied depending on the task and specific object (summarized in Table 3.6) were set as per by Lavoie et al. (2018), and are intentionally liberal because of previous observations that individuals primarily fixate on task relevant objects (Land & Hayhoe 2001; Lavoie et al. 2018).

3.3.4.5 Areas of Interest

In order to compare eye gaze behaviour between movements and tasks, ‘Current’ and ‘Future’ Areas of Interest (AOIs) were defined for each movement phase of each task. In general, the ‘Current’ AOI included an object or target relevant to the current action, while the ‘Future’ AOI was defined as the object or target that the hand will act on next after the current action is complete (in accordance with Lavoie et al. 2018). General rules for defining the AOIs in a given movement phase are provided in Table 3.7. The participant’s end effector (Reach) combined with the object being transported (Transport) by the participant were also considered a separate AOI (‘Hand Only’ AOI) during the Reach and Transport phases. For the current analysis, the ‘Future’ AOI was included because it was required in the definition of the ‘Hand Only’ AOI. However, fixations to ‘Future’ were not analyzed further, as they had been observed to be rare even in able-bodied individuals (Lavoie et al. 2018).

Table 3.7: General criteria for defining ‘Current,’ ‘Future,’ and ‘Hand Only’ areas of interest.

Phase	Current Area of Interest	Future Area of Interest	Hand Only Area of Interest
Reach	Object to be picked-up or target it is set on	Drop-off target	Hand and not the current or future areas of interest
Grasp	Object to be picked-up or target it is set on	Drop-off target	N/A
Transport	Drop-off target	If movement followed by a Home phase: home target, otherwise: next object to be picked-up or target it is set on	Hand or object being transported and not the current or future areas of interest
Release	Object being dropped-off or drop-off target	If movement followed by a Home phase: home target, otherwise: next object to be picked-up or target it is set on	N/A

Fixations to AOIs were calculated using logical operations on segment data and object fixation data. For example, during the first Reach phase in the Cup Transfer Task, the ‘Current’ AOI was defined as the Near (Green) Cup and the starting target that it was placed on, so fixation to the ‘Current’ AOI during Reach 1 or the Cup Transfer Task would be defined as:

Reach 1 Fixation to 'Current' = Reach 1 **AND** (Fixation to Green Cup **OR** Fixation to Green Cup Target 1)

3.3.5 Time Normalization

For the purposes of presenting average representations of time series data across task trials, and for the calculation of one outcome metric, some of the time series data were time-normalized. The specific time series data columns which were included in this processing step were: the position and velocity of the participant's terminal device virtual object centroid, as well as grip aperture (distance between the two motion capture markers on the split-hook). Because of variability in the amount of time spent in different phases and movements in the task, the data were time normalized (resampled to 100 data samples) for each Reach-Grasp and Transport-Release movement segment within the task. These individual time-normalized segments could then be averaged across a participant's task trials. To plot a representation of the complete time series, these time-normalized and averaged segments were combined again and resampled into a complete trial (with 1000 data samples) based on average segment lengths.

3.4 Outcome Metrics

The dependant measures which were calculated using the processed trial data are described in the sections below and summarized in Table 3.8.

3.4.1 Duration

The total time (in seconds) required to complete the tasks was calculated using events in the data which were identified during the segmentation process described in section 3.3.4.2. Total trial time was defined as the time from the onset of the first movement (beginning of Reach 1) to the time when the end effector returns to the 'home' position at the end of the final movement. In addition, durations of each of the Reach, Grasp, Transport and Release phases were calculated.

3.4.2 Eye Gaze Fixation

3.4.2.1 Percent Fixation

The amount of each phase which was spent fixating on a given AOI was calculated and represented as a percentage. Percent Fixation was defined as the number of frames for which a fixation to a given AOI was detected during a specific phase (section 3.3.4.5), divided by the total number of frames in that phase (section 3.3.4.2), multiplied by 100. This was calculated for the 'Current' and 'Hand Only' AOIs in each Reach, Grasp, Transport and Release phase. Average Percent Fixations presented in the tables in the Results Chapter and Appendices are calculated based only on trials where a fixation to a particular AOI did occur (i.e., they represent Percent Fixation *when fixated*, not overall). Average Number of Fixations (see section 3.4.2.3) should be considered to provide insight into how often an AOI was fixated.

3.4.2.2 Target Locking Strategy

A Target Locking Strategy metric (Parr et al. 2017) was calculated as the difference between Percent Fixation to the 'Current' AOI and Percent Fixation to the 'Hand Only' AOI for Reach and Transport phases.

3.4.2.3 Number of Fixations

The number of distinct times that the 'Current' and 'Hand Only' AOIs were fixated was calculated for each Reach, Grasp, Transport and Release phase. Note that 'Number of Fixations' was calculated after gaps and fixations less than 100 ms long had been filled and deleted, respectively. Because it is possible for blinking and jitter in the gaze vector to artificially increase Number of Fixations, fixations to 'Current' and 'Hand Only' should be interpreted together to detect a true glance back-and-forth strategy.

3.4.3 Eye-Hand Latency

A set of measures was developed in order to quantify the temporal relationship between hand movements and gaze behaviour: Eye Arrival Latency Before Grasp, Eye Arrival Latency at Pick-up, Eye Leaving Latency at Pick-up, Eye Arrival Latency at Drop-off, Eye Leaving Latency at Drop-off and Eye Leaving Latency After Release. In general, these metrics measure the extent to which the eyes lead the hand during the functional tasks, and have been defined such that the outcome will be positive if an individual's gaze arrives at or leaves an area of interest before the hand arrives at or leaves that same area of interest, and negative if the reverse is true. The definitions for these metrics were based on those established in (Lavoie et al. 2018) with some modifications to improve their robustness, and two additional measures established to further clarify the behaviour of prosthesis users.

For the purposes of these definitions a "continuous look" is defined as a period of eye gaze fixation on an AOI which was not interrupted by a fixation to another task-relevant target, but may be interrupted by an absence of any fixation (Figure 3.11). This approach should account for blinking and jitter in the gaze vector when calculating the eye-hand latency metrics.

Also, for the purposes of these definitions, a movement is defined as a sequence of Reach-Grasp-Transport-Release and sometimes Home phases. All movements in the Pasta Box Task as well as movements 2 and 4 in the Cup Transfer Task included a Home phase after Release, while movements 1 and 3 in the Cup Transfer Task did not. This is in contrast to other measures, where Home phases were ignored, and not included in the analysis.

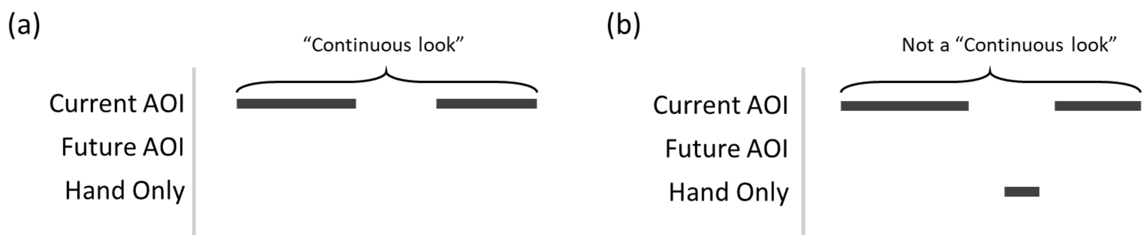

Figure 3.11: Visual representation of the definition of a “continuous look” for the purposes of the eye-hand latency outcome metrics. (a) depicts a scenario in which a fixation to an AOI is interrupted by an absence of fixation, in which case the period from the start of the first fixation to the end of the second fixation would be considered a “continuous look.” (b) depicts a scenario in which a fixation to a particular AOI is interrupted by a fixation to a different AOI, in which case the two fixations would not be considered a “continuous look.”

3.4.3.1 Eye Arrival Latency at Pick-Up

For a given movement, Eye Arrival Latency at Pick-up (EAL_{Pickup}) is defined as the time of eye gaze arrival at the pick-up AOI relative to the time of Transport start. Where the time of eye gaze arrival at the pick-up AOI is defined as the start of the last “continuous look” to the pick-up location or object being picked up during the Reach or Grasp phases. If there is no look to those areas of interest during Reach or Grasp, then it is defined as the first look to the hand or object in flight during Transport. EAL_{Pickup} is positive if an individual’s gaze arrived at the pick-up AOI before the start of Transport, and negative if it arrived after.

3.4.3.2 Eye Arrival Latency Before Grasp

In Lavoie et al. 2018, only one measure was calculated to quantify the extent to which eye gaze leads the hand before object pick-up: Eye Arrival Latency at Pick-up, as described above. However, because we expected prosthesis users to have longer grasp phases than able-bodied individuals, we wished to further distinguish between eye arrival latency relative to the start of object movement, and eye arrival latency relative to the start of hand-object interaction. Therefore, Eye Arrival Latency Before Grasp (EAL_{Grasp}) is defined as the time of eye arrival at the pick-up AOI (as defined in section 3.4.3.1) relative to the time of Grasp start. EAL_{Grasp} is positive if an individual’s gaze arrived at the pick-up AOI before the start of Grasp, and negative if it arrived after. Consequently, EAL_{Grasp} represents the amount of time between eye arrival at the pick-up AOI, and an individual beginning to interact with an object with their hand or end effector, while EAL_{Pickup} represents the amount of time between eye arrival and an individual being confident enough in their grasp to pick the object up.

3.4.3.3 Eye Leaving Latency at Pick-Up

Eye Leaving Latency at Pick-up (ELL_{Pickup}) is defined as the time of eye leaving at pick-up, relative to the time of Transport start. Where the time of eye leaving at pick-up is defined by the end of the “continuous look” to the pick-up location, object being picked up or hand and object in transport, that was initiated by eye arrival at pick-up (as defined in section 3.4.3.1). ELL_{Pickup} is negative if the eyes leave the pick-up location after transport start and positive if the eyes leave the pick-up location before Transport starts.

3.4.3.4 Eye Arrival Latency at Drop-Off

Eye Arrival Latency at Drop-off ($EAL_{Dropoff}$) is defined as the time of eye arrival at drop-off relative to the time of transport end. Where the time of eye arrival at drop-off is defined as the start of the last "continuous look" to the drop-off location before transport end, OR the start of the first look after transport end. $EAL_{Dropoff}$ will be positive if the look starts before Transport ends, and negative if the look starts after Transport ends.

3.4.3.5 Eye Leaving Latency at Drop-off

Eye Leaving Latency at Drop-off ($ELL_{Dropoff}$) is defined as the time of eye leaving at drop-off, relative to the end of transport. Where eye leaving at drop-off is defined as the end of the "continuous look" to the drop-off target or object being dropped-off, that was initiated by eye arrival at the drop-off location (as defined in section 3.4.3.4). $ELL_{Dropoff}$ is negative if the eyes leave the drop-off location after Transport ends, and positive if the eyes leave the drop-off location before transport ends.

3.4.3.6 Eye Leaving Latency After Release

Eye Leaving Latency After Release ($ELL_{Release}$) is defined as the time of eye leaving the drop-off AOI (as defined in section 3.4.3.5) relative to the time of Release end. This is the second metric which was added to the definitions established in Lavoie et al. 2018. Again, it is to further clarify the behaviour of prosthesis users who are expected to spend more time in the Release phases of the movement. $ELL_{Release}$ is positive if eye gaze leaves the drop-off location before Release ends, and negative if gaze lingers on the drop-off location after Release ends.

3.4.4 End Effector Movement

Metrics pertaining to the movement of the participant's terminal device were calculated for combined movement segments of Reach-Grasp and Transport-Release instead of individual Reach, Grasp, Transport and Release phases, as these functional movement segments are more informative when examining movements if the hand/end effector.

3.4.4.1 Hand Distance Travelled

The overall distance traveled by the centroid of the virtual hand object was calculated for each Reach-Grasp and Transport-Release movement segment.

3.4.4.2 Hand Trajectory Variability

Between-trial variability in end effector trajectory was quantified using the time-normalized data for the terminal device virtual object centroid position. Between-trial 3D standard deviation was calculated for each time-normalized data point as the mean of the standard deviation in the X, Y, and Z directions. For each Reach-Grasp and Transport-Release segment, the maximum standard deviation in terminal device position was taken as the Hand Trajectory Variability (Valevicius et al. 2018).

3.4.4.3 Number of Movement Units

A movement unit was defined as a local peak in terminal device velocity. The Number of Movement Units within a given Reach-Grasp or Transport-Release segment was calculated as the number of zero-crossings in the terminal device acceleration profile, where acceleration transitions from positive to negative (Valevicius et al. 2018).

3.4.4.4 Peak Hand Velocity

The maximum speed of the participant's terminal device was determined for each Reach-Grasp and Transport-Release segment, using the velocity profile of the centroid of the terminal device virtual object.

3.4.4.5 Percent to Peak Hand Velocity

The time point at which peak hand velocity was reached was expressed as a percentage of each Reach-Grasp and Transport-Release movement segment.

3.4.4.6 Percent to Peak Hand Deceleration

The time point at which minimum hand acceleration (peak deceleration) was reached was expressed as a percentage of each Reach-Grasp movement segment.

3.4.4.7 Percent to Peak Grip Aperture

For each Reach-Grasp movement segment, the point at which the distance between the two markers on the participant's split hook reached a maximum was identified and expressed as a percentage of the total length of the Reach-Grasp movement segment.

Table 3.8: Summary of all outcome metrics calculated for the current analysis

Metric	Abbreviation	Definition
Trial Duration		Time from start of first reach to end of final return to home
Phase Durations		Durations of all phases (Reach, Grasp, Transport, Release) in the task
Relative Phase Durations		Duration of each phase relative to the length of its respective movement, where a movement is defined as one Reach-Grasp-Transport-Release sequence
Percent Fixations to Current		Percentage of each phase during which eye gaze is fixated on the 'Current' AOI as defined in section 3.3.4.5
Percent Fixations to Hand Only		Percentage of each phase during which eye gaze is fixated on the 'Hand Only' AOI as defined in section 3.3.4.5
Target Locking Strategy	TLS	Percent Fixation to the 'Current' AOI – Percent Fixation to the 'Hand Only' AOI for Transport and Release phases (Parr et al. 2017)
Number of Fixations to Current		Number of distinct instances in each phase when eye gaze is fixated on the 'Current' AOI, as defined in section 3.3.4.5
Number of Fixations to Hand Only		Number of distinct instances in each phase when eye gaze is fixated on the 'Hand Only' AOI, as defined in section 3.3.4.5
Eye Arrival Latency Before Grasp	EAL_{Grasp}	The time of gaze arrival at the object pick-up AOI relative to the time of Grasp start (positive if gaze arrives before Grasp start)
Eye Arrival Latency at Pick-up	EAL_{Pickup}	The time of gaze arrival at the object pick-up AOI relative to the time of Transport start (positive if gaze arrives before Transport start)
Eye Leaving Latency at Pick-up	ELL_{Pickup}	The time of gaze leaving the pick-up AOI or hand relative to the time of Transport start (positive if gaze leaves before Transport start)
Eye Arrival Latency at Drop-off	$EAL_{Dropoff}$	The time of gaze arrival at the drop-off AOI relative to the time of Transport end (positive if gaze arrives before Transport end)
Eye Leaving Latency at Drop Off	$ELL_{Dropoff}$	The time of gaze leaving the drop-off AOI relative to the time Transport end (positive if gaze leaves before Transport end)
Eye Leaving Latency After Release	$ELL_{Release}$	The time of gaze leaving the drop-off AOI relative to the time of release end (positive if gaze leaves before release end)
Hand Distance Travelled		Total distance traversed by the centroid of the terminal device for each Reach-Grasp and Transport-Release segment
Hand Trajectory Variability		Maximum between-trial standard deviation in terminal device 3D position for each Reach-Grasp and Transport-Release segment
Number of Movement Units		Number of positive-to-negative zero crossings in the acceleration profile of the terminal device for each Reach-Grasp and Transport-Release segment
Peak Hand Velocity		Maximum velocity of the centroid of the terminal device for each Reach-Grasp and Transport-Release segment
Percent to Peak Hand Velocity		Point of maximum terminal device velocity expressed as percentage of each Reach-Grasp and Transport-Release segment

Percent to Peak Hand Deceleration	Point of minimum terminal device acceleration expressed as percentage of each Reach-Grasp and Transport-Release segment
Percent to Peak Grip Aperture	Point of maximum grip aperture expressed as percentage of each Reach-Grasp and Transport-Release segment

3.5 Interpretation Methods

3.5.1 Comparison with Normative Data

Outcomes for transradial and transhumeral body-powered prosthesis users were compared to a set of normative metrics, which had been previously established by Lavoie et al. (2018) and Valevicius et al. (2018). In these studies, to establish these normative outcomes, 20 able-bodied individuals were recruited (11 male; 18 right-handed; age: 25.8 ± 7.2 years; height: 174 ± 8 cm; mean ± standard deviation). However, due to poor gaze calibrations or trial pupil data, one data set was discarded for the Cup Transfer Task, and three were discarded for the Pasta Box Task.

Because of the small number of participants recruited for the current study, outcome metrics for each prosthesis user were individually compared to the normative data. For each outcome metric, a 'normative range' was defined as the normative mean ± two standard deviations (SD). For the prosthesis user participants, individual outcomes which fell outside of the normative range were identified. In the tabular presentation of the results in Chapter 4 and the appendices, these outcomes are identified by a red (higher value than normative) or blue (lower value than normative) highlighted cell. After examining the behaviour of each prosthesis user participant as a case study, generalizations were made to characterize the behaviour of the TR and TH BP users, where appropriate.

3.5.2 Comparison with Myoelectric Prosthesis Users in the Literature

We were interested in comparing the results of this study with previous characterizations of myoelectric prosthesis user eye gaze behaviour from the literature. Previously reported metrics which offered a potentially valid comparison with our data were identified based on two criteria:

1) The description of the outcome metric was consistent with a metric which had been included in our analysis, or which we could calculate using our data
2) The study presented normative values for the metric which were comparable with the normative data used in this study (section 3.5.1)

Across the examined literature, the only outcome measure which met these criteria was Parr et al.'s (2017) Target Locking Strategy (TLS), which we recognized as the difference between our Percent Fixation to the 'Current' AOI and Percent Fixation to the 'Hand Only' AOI (section 3.4.2.1). Specifically, results for able-bodied individuals presented by Parr et al. were consistent with our normative data in the Reach phases of the Cup Transfer Task. TLS was not consistent between the Transport phases of our tasks and the coin 'lift-and-drop' phases of Parr's tasks, nor was Parr's TLS in Reach comparable with our Pasta Box Task, likely because some targets started out of the participant's field of view (Lavoie et al. 2018).

Parr et al. did not report exact values for TLS in their publication, but from reading their bar chart, it can be concluded that their participants had an average TLS during Reach of approximately 80% when using their anatomic hand and just under 40% when using the simulated myoelectric prosthesis. When TLS in Reach was calculated for our normative data on the Cup Transfer Task, values ranged from 69 to 92%, which indicates a larger variability than was observed by Parr et al., but encompasses a range which is roughly centered on their average TLS of 80%. Thus, TLS was calculated for the Reach phases of the Cup Transfer Task in order to compare with Parr et al. (2017).

Chapter 4. Results

4.1 Transradial Body-Powered Prosthesis Users

Despite the expected variability between the transradial (TR) body-powered (BP) prosthesis users, some consistent trends in their behaviour relative to the normative data set emerged. The TR BP users consistently took longer than able-bodied individuals to perform both the Cup Transfer Task and Pasta Box Task. They also demonstrated less smooth movement trajectories (higher Number of Movement Units), and generally had higher between-trial variability in their end effector trajectories. The TR BP users also tended to fixate more on objects they were manipulating as they were grasping them, beginning to transport them, and after they had released them. However, the percentage of time which they were able to spend looking ahead at upcoming pick-up and drop-off targets mostly fell within the range of normative behaviour. In fact, once they were confident enough to transition their gaze to lead their hand, it did not appear that they would glance back. These and other results will be elaborated upon in the following sections.

Detailed eye behaviour and end effector metric reports for each individual prosthesis user are provided in Appendix B (P66), Appendix C (P14), Appendix D (P85), Appendix E (P50), and Appendix F (P94).

4.1.1 Cup Transfer Task

Visualizations summarizing the performance of two of the TR BP users (P14 and P50) for the Cup Transfer Task relative to the normative data set are provided in Figure 4.1. These figures provide a visual comparison of trial and phase durations as well as eye gaze fixation behaviour and terminal device and object velocity profiles (Lavoie 2018). The two TR users whose behaviour is shown in Figure 4.1 represent one of the users whose behaviour was most similar to normative on this task (P14), and one of the users whose outcome metrics were farthest from normative (P50).

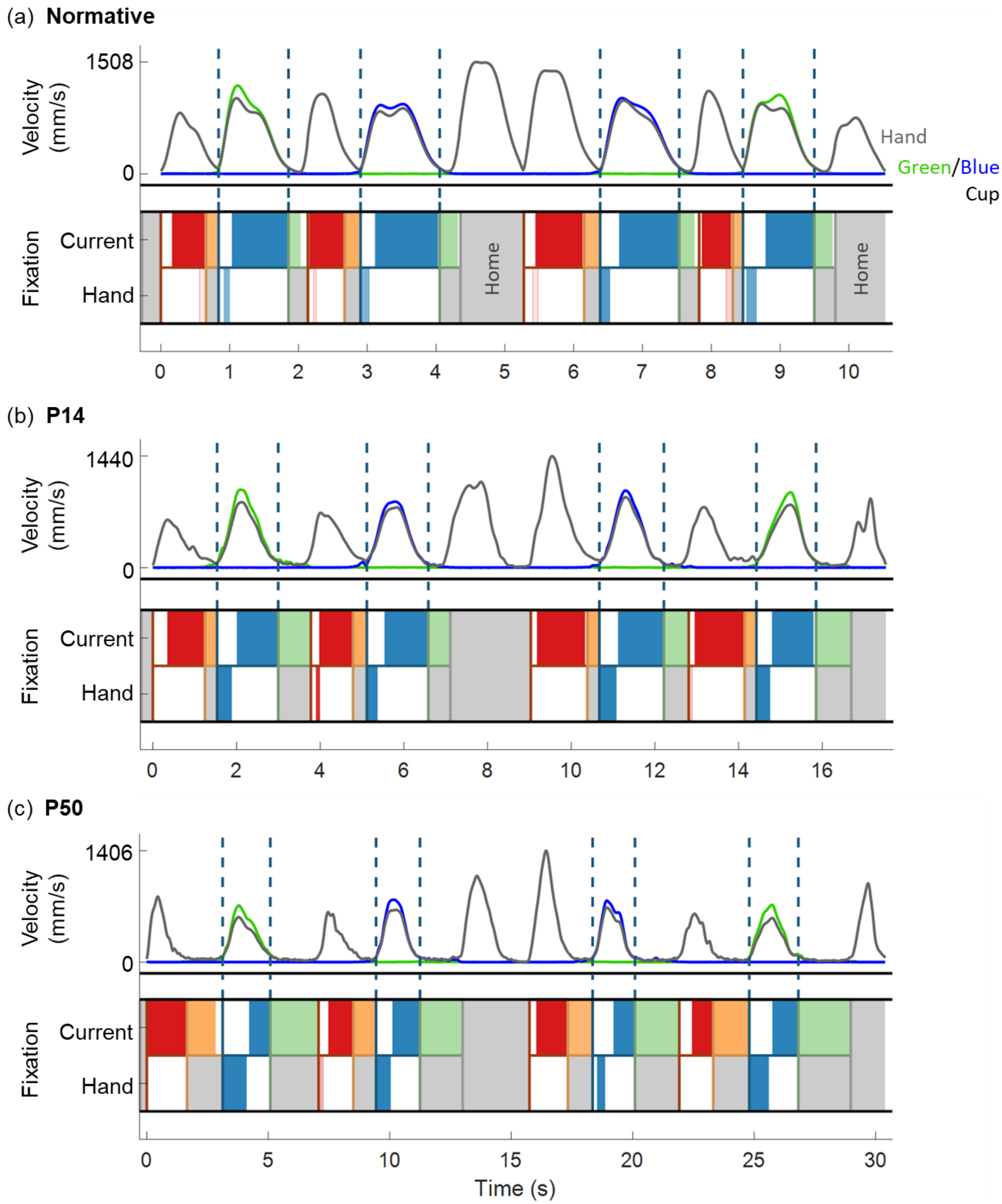

Figure 4.1: Visualizations of average end effector and object velocities as well as eye gaze fixation behaviour for two TR BP prosthesis users performing the Cup Transfer Task, compared with normative behaviour: (a) normative data set, (b) P14, (c) P50. Velocity plots are for hand (grey) and objects (green cup and blue cup). Fixation plots represent Percent Fixations to 'Current' and 'Hand Only' AOIs throughout each task phase: Reach (red), Grasp (orange), Transport (blue), and Release (green). Opacity level of fixation plots represents probability of fixation. The entire task is plotted with time along the x-axis.

From these summary figures, a number of things can be observed. From the timelines, it can be seen that both P14 and P50 took longer than the able-bodied individuals to perform The Cup Transfer task (approximately 17 and 30 sec respectively, compared to less than 10 s for normative). However, P14's (Figure 4.1b) relative phase durations appeared to be closer the normative cohort's, while P50 (Figure 4.1c) appeared to spend disproportionate amounts of time in the grasping phase (as evidenced by the disproportionally increased duration of orange sections) and releasing the cups (green portion). The fixation sections of Figure 4.1 indicated that P14 and P50 were more likely to fixate on their terminal device during Transport than able-bodied individuals (greater opacity of blue sections in the row for fixations to hand), and often fixated on it for a greater percentage of Transport (greater proportion of blue sections in the row for fixations to hand).

From examining the velocity profiles in Figure 4.1 (top traces), both P14 and P50 appear to have increased movement units (local maxima) compared with able-bodied individuals. These small velocity peaks mostly occur in the Grasp and Release phases of the movements, with Reach and Transport movements still appearing to be relatively smooth especially for P14, while P50's velocity profiles were less smooth in some Reach phases. Specific metrics relating to Figure 4.1 and other measures of visuomotor behaviour are presented for all five of the TR BP users in the following sections.

4.1.1.1 Task Performance

General performance metrics of Total Trial Duration and Percent Success Rate (percentage of trials completed without errors) for the TR BP prosthesis users on the Cup Transfer Task are summarized in Table 4.1. Specific phase durations are shown in Figure 4.2 and relative phase durations are compared in Table 4.2.

Table 4.1: Mean Total Trial Duration and Percent Success Rate for the TR BP prosthesis users performing the Cup Transfer Task compared with normative data. Standard deviations for Trial Duration are shown in brackets (between-participant SD for normative data, and between-trial SD for prosthesis users). Highlighted cells indicate prosthesis user outcomes which were more than two SD from the normative mean: red = higher value than normative, blue = lower.

	Norm	P66	P14	P85	P50	P94
Trial Duration (s)	10.5 (1.3)	17.9 (1.0)	17.5 (1.1)	20.1 (1.1)	30.4 (1.0)	24.9 (1.1)
Percent Success Rate (%)	89 –	90 –	70 –	90 –	70 –	100 –

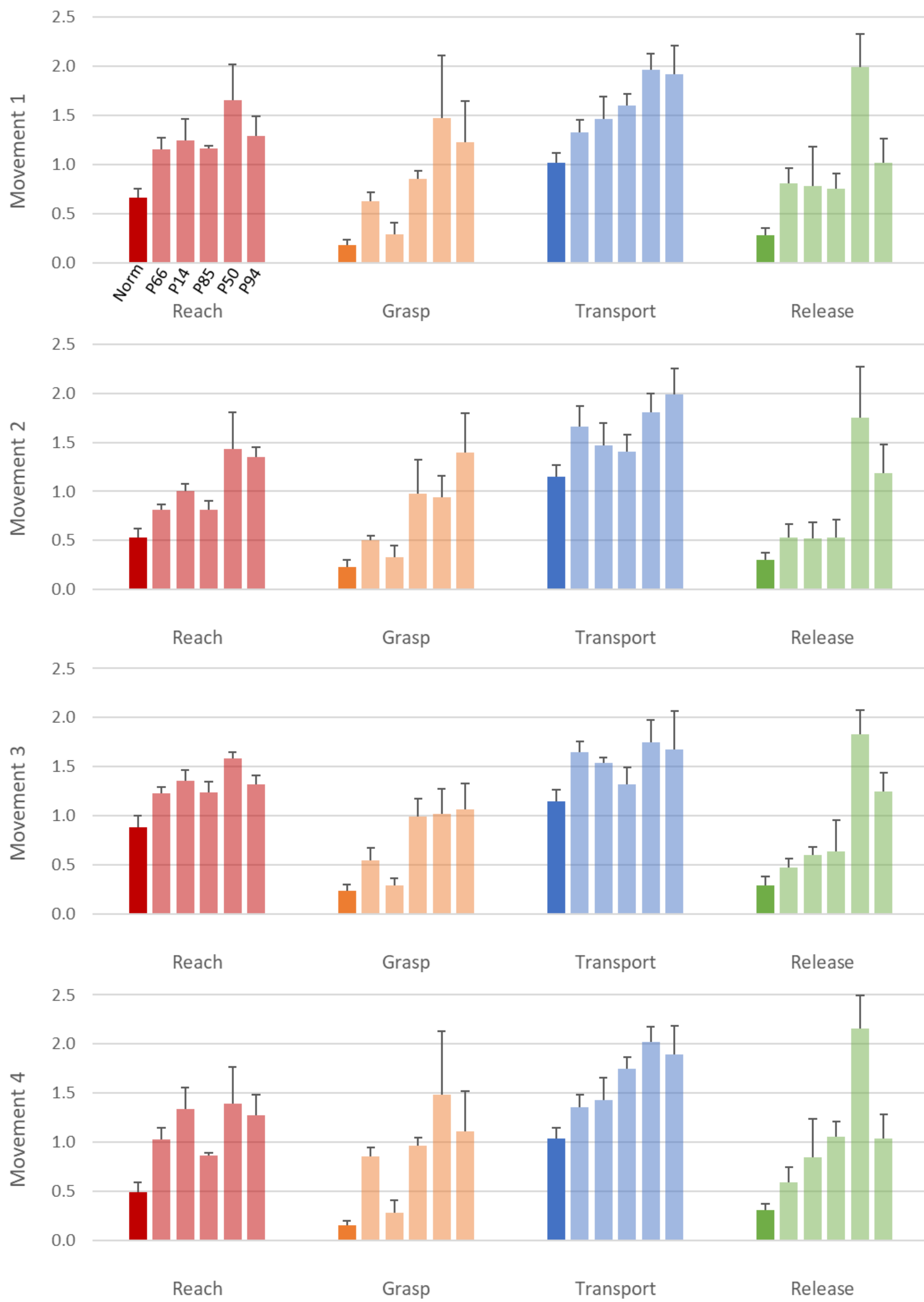

Figure 4.2: Average phase durations for the TR BP prosthesis users (semi-transparent bars, from left to right: P66, P14, P85, P50, P94) performing the Cup Transfer Task, compared with normative data (opaque bars).

All of the five TR BP prosthesis users' average trial durations were more than two standard deviations above the normative mean for the Cup Transfer Task (Table 4.1). Four of the five participants spent a disproportionate amount of time in the Grasp phases (relative phase duration of Grasp phases was more than 2 standard deviations above normative as seen in Table 4.2), while the other participant (P14) was able to complete the grasp phases nearly as quickly as the able-bodied participants, but spent a disproportionate amount of time in some Reach phases of the task. This faster grasping strategy appeared to be associated with less precision in grip aperture. While most of the participants with a TR amputation presented similar grip aperture profiles with minimal opening of the terminal device (hook) to grip the cup (Figure 4.3), P14 appeared to open their grasp more widely when grasping and releasing the cups, and exhibited more variability in grip aperture (Figure 4.3c and Table C.5 in Appendix C). P14's increase in speed (in Grasp and overall) was also associated with an increase in errors, as they were one of two participants with the most errors for this task (Table 4.1), with two trials where they did the movement sequence incorrectly, and one with bead spillage (Table C.2 in Appendix C).

Table 4.2: Relative Phase Durations for the TR BP prosthesis users performing the Cup Transfer Task. Phase durations for the Reach (R), Grasp (G), Transport (T), and Release (RL) phases are expressed as a percentage of the respective movement (R-G-T-RL). Standard deviations are shown in brackets (between-participant SD for normative data, and between-trial SD for prosthesis users). Highlighted cells indicate prosthesis user outcomes which were more than two SD from the normative mean: red = higher value than normative, blue = lower.

Relative Phase Duration (% of movement)							
		Norm	P66	P14	P85	P50	P94
Mvmt 1	R	31 (2)	29 (3)	33 (6)	27 (2)	24 (6)	24 (4)
	G	8 (2)	16 (3)	8 (3)	19 (1)	20 (8)	22 (6)
	T	48 (2)	34 (3)	39 (5)	37 (2)	28 (4)	35 (4)
	RL	13 (2)	20 (3)	20 (8)	17 (3)	28 (3)	19 (5)
Mvmt 2	R	24 (2)	23 (1)	30 (2)	22 (2)	24 (4)	23 (2)
	G	10 (2)	14 (1)	10 (3)	26 (7)	16 (4)	23 (6)
	T	52 (3)	47 (3)	44 (4)	38 (6)	31 (4)	34 (4)
	RL	14 (3)	15 (3)	16 (5)	14 (4)	29 (6)	20 (4)
Mvmt 3	R	34 (2)	32 (2)	36 (3)	30 (4)	26 (2)	25 (3)
	G	9 (2)	14 (2)	8 (2)	24 (3)	16 (3)	20 (4)
	T	45 (2)	42 (3)	41 (2)	32 (4)	28 (4)	31 (5)
	RL	11 (3)	12 (2)	16 (2)	15 (7)	30 (3)	24 (4)
Mvmt 4	R	25 (3)	27 (3)	34 (4)	19 (3)	20 (5)	24 (3)
	G	7 (2)	22 (7)	7 (2)	21 (5)	21 (4)	21 (5)
	T	53 (3)	36 (6)	37 (5)	38 (4)	29 (3)	36 (6)
	RL	15 (4)	16 (3)	22 (3)	23 (4)	30 (6)	19 (6)

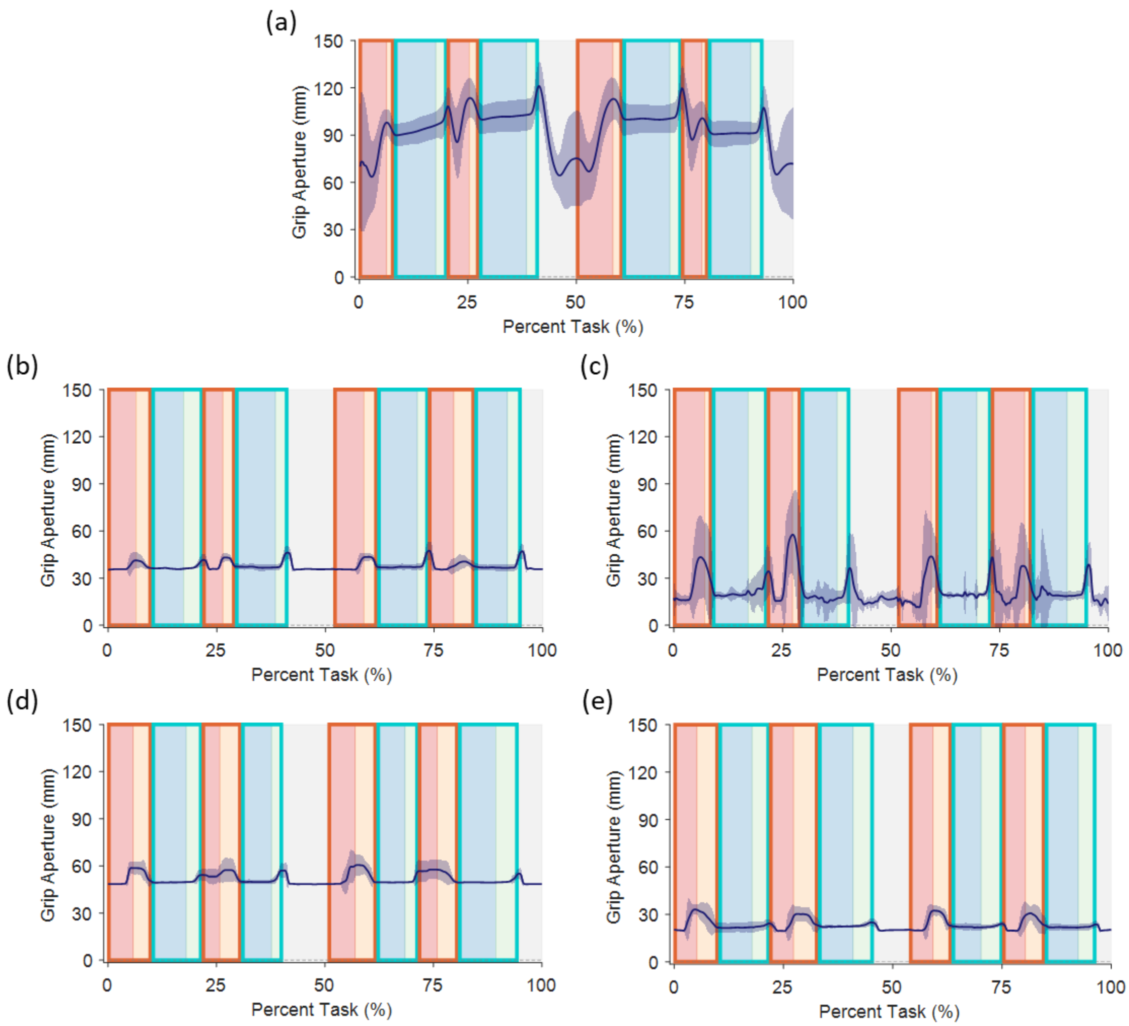

Figure 4.3: Average grip aperture profiles for the TR BP prosthesis users while performing the Cup Transfer Task compared with normative data: (a) normative data set, (b) P66, (c) P14, (d) P85, (e) P94. Shading shows ± one standard deviation (between-participant SD for normative data, and between-trial SD for prosthesis users). Task phases are shown: Reach (red), Grasp (orange), Transport (blue), and Release (green). The grip aperture profile for P50 is not shown, as the markers on their split-hook terminal device were not tracking reliably in the first two movements of the Cup Transfer Task.

4.1.1.2 Eye Gaze Fixation

The TR BP prosthesis users' Percent Fixations and Number of Fixations to the Current and Hand Only AOIs during the Reach and Transport phases of the Cup Transfer Task are summarized in Table 4.3 and Table 4.4, respectively. During Grasp and Release phases, the TR users tended to fixate on the 'Current' AOI for 100% or close to 100% of the phase (see Table 4 Appendices B, C, D, E, and F), these values therefore were not included in Table 4.3. This level of fixation to the 'Current' AOI during Grasp and Release was consistently higher than the normative mean, but still within 2 standard deviations for all phases except the first Release phase. Target Locking Strategy for the Reach phases, calculated as Percent Fixation to

Current minus Percent Fixation to the Hand Only in accordance with Parr et al. 2017, is presented in Table 4.5.

Table 4.3: Mean Percent Fixations for the TR BP prosthesis users to the Current and Hand Only AOIs during the Reach (R) and Transport (T) phases Cup Transfer Task. Standard deviations are shown in brackets (between-participant SD for normative data, and between-trial SD for prosthesis users). Highlighted cells indicate prosthesis user outcomes which were more than two SD from the normative mean: red = higher value than normative, blue = lower.

Mean Percent Fixations (When Fixated) (%)								
			Norm	P66	P14	P85	P50	P94
Current AOI	Mvmt 1	R	72 (15)	58 (3)	73 (8)	75 (11)	97 (3)	88 (17)
		T	79 (11)	69 (8)	67 (3)	71 (5)	44 (3)	60 (9)
	Mvmt 2	R	93 (7)	84 (9)	79 (7)	96 (6)	73 (10)	76 (18)
		T	80 (12)	53 (8)	71 (8)	63 (8)	63 (13)	61 (8)
	Mvmt 3	R	78 (15)	87 (15)	86 (17)	79 (22)	78 (13)	84 (21)
		T	74 (11)	51 (5)	71 (8)	67 (5)	51 (6)	58 (9)
	Mvmt 4	R	85 (12)	76 (11)	90 (97)	82 (6)	64 (12)	87 (10)
		T	66 (15)	46 (13)	69 (8)	48 (4)	53 (4)	52 (10)
Hand Only AOI	Mvmt 1	R	14 (7)	0 (0)	0 (0)	0 (0)	0 (0)	30 (11)
		T	8 (5)	24 (9)	24 (7)	24 (6)	48 (7)	27 (10)
	Mvmt 2	R	8 (4)	15 (8)	9 (12)	4 (2)	8 (9)	13 (9)
		T	10 (4)	39 (9)	17 (8)	27 (10)	33 (13)	27 (11)
	Mvmt 3	R	7 (5)	0 (0)	0 (0)	4 (0)	0 (0)	0 (0)
		T	12 (6)	34 (8)	26 (5)	20 (2)	18 (8)	30 (5)
	Mvmt 4	R	17 (12)	9 (2)	7 (0)	0 (0)	0 (0)	6 (5)
		T	14 (10)	50 (17)	22 (5)	41 (7)	40 (7)	37 (9)

The TR prosthesis users showed similar patterns of eye gaze behaviour. Their Percent Fixations to the ‘Current’ target fell within the range of the normative average ± 2 standard deviations in the majority of the task phases (Table 4.3). All of these participants tended to follow their end effectors with their gaze as they started to transport the cups over the barrier, as evidenced by higher percent fixations to the ‘Hand Only’ AOI during transport (Table 4.3) and longer ELL_{Pickup} values (see Table 4.6 in section 4.1.1.3). Mean Number of Fixations to hand in Transport of 0.9 or greater (Table 4.4) indicated that this was a consistent behaviour which occurred in almost all trials. The amount of time during Transport for which the TR BP users watched the cup/terminal device varied between participants and movements (average Percent Fixations to Current during Transport ranged from 17% to 50%). This behaviour was generally associated with a reduction in the percentage of Transport that they were able to fixate on the drop-off (‘Current’) target (Table 4.3). However, there were only two participants for which this decrease brought them below the normative range for Percent Fixation to ‘Current’ in some Transport phases (P66 and P50).

None of the TR BP prosthesis users appeared to employ a strategy of glancing back and forth between their end effector and the 'Current' target during Reach or Transport phases. There were some instances where they had a higher average Number of Fixations to the 'Hand Only' or 'Current' AOI than the normative average (Table 4.4); however, these did not appear to indicate a true glance-back strategy as increased average Number of Fixations to 'Hand Only' did not correspond to an equivalent increase in Number of Fixations to 'Current.'

Table 4.4: Mean Number of Fixations for the TR BP prosthesis users to the Current and Hand Only AOIs during the Reach (R) and Transport (T) phases Cup Transfer Task. Standard deviations are shown in brackets (between-participant SD for normative data, and between-trial SD for prosthesis users). Highlighted cells indicate prosthesis user outcomes which were more than two SD from the normative mean: red = higher value than normative, blue = lower.

Mean Number of Fixations								
			Norm	P66	P14	P85	P50	P94
Current AOI	Mvmt 1	R	1.0 (0.1)	1.0 (0.0)	1.0 (0.0)	1.0 (0.0)	1.0 (0.0)	1.0 (0.0)
		T	1.0 (0.0)	1.0 (0.0)	1.0 (0.0)	1.1 (0.3)	1.0 (0.0)	1.4 (0.5)
	Mvmt 2	R	1.0 (0.0)	1.0 (0.0)	1.0 (0.0)	1.0 (0.0)	1.0 (0.0)	1.0 (0.0)
		T	1.0 (0.0)	1.0 (0.0)	1.0 (0.0)	1.0 (0.0)	1.0 (0.0)	1.1 (0.3)
	Mvmt 3	R	1.0 (0.1)	1.1 (0.3)	1.4 (0.5)	1.2 (0.4)	1.1 (0.4)	1.2 (0.4)
		T	1.0 (0.0)	1.0 (0.0)	1.1 (0.4)	1.0 (0.0)	1.0 (0.0)	1.1 (0.3)
	Mvmt 4	R	1.0 (0.1)	1.1 (0.3)	1.0 (0.0)	1.0 (0.0)	1.0 (0.0)	1.1 (0.3)
		T	1.0 (0.1)	1.0 (0.0)	1.1 (0.4)	1.0 (0.0)	1.0 (0.0)	1.1 (0.3)
Hand Only AOI	Mvmt 1	R	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.2 (0.4)
		T	0.5 (0.3)	1.0 (0.0)	1.0 (0.0)	1.0 (0.0)	1.1 (0.4)	0.9 (0.3)
	Mvmt 2	R	0.1 (0.1)	0.9 (0.3)	0.9 (0.4)	0.4 (0.5)	0.3 (0.5)	1.2 (0.4)
		T	0.6 (0.3)	1.0 (0.0)	1.0 (0.0)	1.0 (0.0)	1.0 (0.0)	1.3 (0.5)
	Mvmt 3	R	0.1 (0.2)	0.0 (0.0)	0.0 (0.0)	0.1 (0.3)	0.0 (0.0)	0.0 (0.0)
		T	0.7 (0.3)	1.3 (0.5)	1.0 (0.0)	1.0 (0.0)	1.9 (0.7)	1.6 (0.7)
	Mvmt 4	R	0.1 (0.2)	0.3 (0.5)	0.1 (0.4)	0.0 (0.0)	0.0 (0.0)	0.2 (0.4)
		T	0.7 (0.4)	1.0 (0.5)	1.0 (0.0)	1.3 (0.7)	1.1 (0.4)	1.6 (0.5)

All five of the TR BP participants had at least one Reach phase (most commonly in movement 2) in which their Number of Fixations to Hand Only was higher than the normative mean. This implies that it was more common for them to look at their end effector during Reach than it was for able-bodied individuals. However, most of these values were still below one, indicating that this behaviour was not consistent, and only occurred in some trials. In addition, there was only one participant (P94) for whom these fixations were long enough that Percent Fixation (when fixated) to the Hand in Reach was outside of the normative range.

The TR BP users' TLS values during Reach were mostly within the normative range, except in movement 2 (Table 4.5), and were consistently above the 40% which Parr et al. (2017) had observed for individuals using a simulated myoelectric prosthesis.

Table 4.5: Mean Target Locking Strategy (TLS) outcomes (calculated as Percent Fixation to Current – Percent Fixation to Hand Only, as per Parr et al. 2017) for the TR BP prosthesis users during the Reach phases of the Cup Transfer Task. Standard deviations are shown in brackets (between-participant SD for normative data, and between-trial SD for prosthesis users). Highlighted cells indicate prosthesis user outcomes which were more than two SD from the normative mean: red = higher value than normative, blue = lower.

Mean Target Locking Strategy (%)						
	Norm	P66	P14	P85	P50	P94
Reach 1	69 (18)	58 (3)	73 (8)	75 (11)	97 (3)	81 (30)
Reach 2	92 (9)	71 (15)	71 (17)	94 (7)	70 (12)	63 (26)
Reach 3	76 (17)	87 (16)	86 (17)	79 (22)	78 (13)	84 (21)
Reach 4	81 (21)	73 (12)	89 (9)	82 (6)	64 (12)	86 (11)

4.1.1.3 Eye-Hand Latency

Eye-Hand Latency outcomes for the TR BP prosthesis users during the Cup Transfer Task are summarized in Table 4.6.

When picking up the cups, the TR BP prosthesis users' Eye Arrival Latencies relative to both Transport start and Grasp start (EAL_{Pickup} and EAL_{Grasp}) were consistently greater than for the normative population, and mostly more than two standard deviations from the normative mean (Table 4.6). This indicates that they looked at the pick-up target for longer before initiating Grasp and Transport than the able-bodied individuals. This is expected since the TR users generally spent longer in the Reach and Grasp phases, but fixated on the 'Current' AOI for a similar percentage of Reach.

After pick-up, the TR BP users tended to continue to look at the cup and/or their terminal device for longer than able-bodied individuals (more negative ELL_{Pickup} values), as was mentioned in section 4.1.1.2.

Before drop-off, Eye Arrival Latency ($EAL_{Dropoff}$) values were slightly greater than normative values, but closer to normative than EAL_{Pickup} (mostly within 2 standard deviations). However, because the TR prosthesis users had longer transport phases, this would imply that they were looking at the drop-off target for a smaller percentage of transport, as stated in in section 4.1.1.2.

Table 4.6: Eye-Hand Latency Metrics for the TR BP prosthesis users during each Movement (M) of the Cup Transfer Task: Eye Arrival Latency before Grasp Start (EAL_{Grasp}); Eye Arrival Latency before Transport Start (EAL_{Pickup}); Eye Leaving Latency after Transport Start (ELL_{Pickup}); Eye Arrival Latency before Transport End ($EAL_{Dropoff}$); Eye Leaving Latency after Transport End ($ELL_{Dropoff}$); and Eye Leaving Latency after Release End ($ELL_{Release}$). Standard deviations are shown in brackets (between-participant SD for normative data, and between-trial SD for prosthesis users). Highlighted cells indicate prosthesis user outcomes which were more than two SD from the normative mean: red = higher value than normative, blue = lower.

Mean Eye-Hand Latency Metrics (s)

			Norm		P66		P14		P85		P50		P94	
Cup Pick-up	EAL_{Grasp}	M 1	0.48	(0.14)	0.67	(0.07)	0.90	(0.14)	0.87	(0.14)	1.60	(0.37)	0.83	(0.75)
		M 2	0.50	(0.10)	0.68	(0.07)	0.80	(0.12)	0.77	(0.10)	1.02	(0.16)	0.90	(0.43)
		M 3	0.70	(0.15)	1.09	(0.19)	1.20	(0.20)	0.97	(0.24)	1.29	(0.24)	1.16	(0.29)
		M 4	0.42	(0.09)	0.76	(0.14)	1.19	(0.21)	0.70	(0.06)	0.86	(0.11)	1.12	(0.16)
	EAL_{Pickup}	M 1	0.66	(0.16)	1.30	(0.08)	1.19	(0.21)	1.72	(0.18)	3.07	(0.53)	2.06	(0.55)
		M 2	0.73	(0.16)	1.18	(0.11)	1.13	(0.19)	1.75	(0.40)	1.95	(0.19)	2.29	(0.55)
		M 3	0.93	(0.19)	1.63	(0.24)	1.49	(0.22)	1.96	(0.35)	2.31	(0.28)	2.22	(0.33)
		M 4	0.57	(0.10)	1.61	(0.32)	1.47	(0.20)	1.66	(0.25)	2.35	(0.34)	2.22	(0.35)
	ELL_{Pickup}	M 1	-0.02	(0.10)	-0.32	(0.11)	-0.35	(0.13)	-0.38	(0.12)	-0.55	(1.18)	-0.50	(0.24)
		M 2	-0.04	(0.10)	-0.70	(0.21)	-0.27	(0.12)	-0.39	(0.17)	-0.61	(0.28)	-0.54	(0.23)
		M 3	-0.06	(0.18)	-0.62	(0.21)	-0.41	(0.07)	-0.28	(0.04)	-0.76	(0.29)	-0.58	(0.31)
		M 4	-0.06	(0.19)	-0.55	(0.44)	-0.33	(0.10)	-0.78	(0.24)	-0.85	(0.11)	-0.71	(0.31)
Cup Drop-off	$EAL_{Dropoff}$	M 1	0.82	(0.15)	0.91	(0.14)	0.98	(0.18)	1.14	(0.09)	0.87	(0.08)	1.26	(0.24)
		M 2	0.94	(0.12)	0.87	(0.11)	1.05	(0.25)	0.88	(0.09)	1.12	(0.20)	1.18	(0.17)
		M 3	0.87	(0.16)	0.84	(0.11)	1.09	(0.12)	0.88	(0.17)	0.88	(0.13)	0.96	(0.24)
		M 4	0.70	(0.17)	0.62	(0.19)	0.95	(0.25)	0.83	(0.09)	1.07	(0.09)	0.96	(0.28)
	$ELL_{Dropoff}$	M 1	-0.15	(0.10)	-0.89	(0.16)	-0.95	(0.35)	-0.75	(0.14)	-2.27	(0.32)	-0.93	(0.34)
		M 2	-0.32	(0.26)	-1.02	(0.21)	-0.81	(0.22)	-0.63	(0.16)	-2.26	(0.56)	-1.33	(0.32)
		M 3	-0.22	(0.11)	-0.65	(0.12)	-0.73	(0.15)	-0.68	(0.36)	-2.33	(0.35)	-1.23	(0.34)
		M 4	-0.34	(0.19)	-0.83	(0.18)	-1.03	(0.14)	-1.27	(0.44)	-2.81	(0.51)	-1.09	(0.41)
	$ELL_{Release}$	M 1	0.14	(0.09)	-0.09[1]	(0.08)	-0.17	(0.05)	0.01	(0.04)	-0.28	(0.05)	0.09	(0.19)
		M 2	-0.02	(0.25)	-0.49	(0.14)	-0.29	(0.09)	-0.10	(0.07)	-0.51	(0.12)	-0.15	(0.19)
		M 3	0.06	(0.11)	-0.18	(0.06)	-0.13	(0.12)	-0.04	(0.14)	-0.50	(0.30)	0.02	(0.23)
		M 4	-0.04	(0.17)	-0.24	(0.10)	-0.18	(0.03)	-0.22	(0.28)	-0.66	(0.19)	-0.05	(0.25)

[1] Although this value $ELL_{Release}$ value was smaller in absolute value than normative, it was negative while the normative mean was positive, indicating lingering gaze instead of eyes leaving before Release end.

After drop-off, the Eye Leaving Latency values relative to Transport end ($EAL_{Dropoff}$) for the TR BP users were generally larger than the normative values, which is consistent with the fact that they spent longer in the Release phases, and continued to look at the cup at its drop-off target for close to 100% of Release. At the end of Release, two of the TR users (P85 and P94) were able to look away from the cup they had dropped off relatively quickly, sometimes even before their end effector was far enough away to trigger the end of Release ($ELL_{Release}$ close to zero or positive). This behaviour was similar to the able-bodied individuals, who on average would look away close to the end of the Release phase and sometimes even before, especially in movements 1 and 3 where they were immediately moving to pick up another cup without a Home phase in between. However, the other TR participants tended to keep their gaze on the released cup even after they had moved their end effector away. The most extreme example of this was P50 whose average $ELL_{Release}$ values ranged from roughly 250 to 650 ms.

4.1.1.4 End Effector Movement

The end effector metrics of Hand Distance Travelled, Hand Trajectory Variability, Number of Movement Units, and Peak Hand Velocity are summarized in Table 4.7. Outcomes relating to Percent to Peak Hand Velocity, Hand Deceleration and Grip Aperture for only the Reach-Grasp segments of each movement are summarized in Table 4.8, while Percent to Peak Hand Velocity for the Transport-Release segments is presented in Table 4.9.

The TR BP prosthesis users mostly had a similar Hand Distance Travelled to normative values, except for P14 and P50, who both had greater hand distance travelled in the Reach-Grasp segments, and were outside of the normative range in Reach-Grasp 1, 3 and 4 (Table 4.7). For P14, this was consistent with the fact that they spent a disproportionate amount of time in the reach phases of the task. For P50, this was consistent with the fact that they took the longest to perform the task overall.

With respect to Number of Movement Units and Hand Trajectory, the TR BP users generally demonstrated increased jerkiness (higher Number of Movement Units) and between-trial variability in their end effector trajectories compared to the normative data set (Table 4.7). There was also substantial variability between the TR BP users for these metrics, especially for Number of Movement Units. The able-bodied individuals had an average of 1 to 2 movement units per Reach-Grasp or Transport-Release segment, while the TR BP user outcomes for this metric ranged from 2 to 19. For the most part, higher Number of Movement Units appeared to correspond with increased Percent Fixation to Hand in Transport, except in the case of P66 who was most similar to normative means in terms of Number of Movement Units, but had some of the highest values for Percent Fixation to Hand in Transport.

With respect to end effector velocity, the TR BP users had peak hand velocities which were generally lower than the normative values (Table 4.7). This is consistent with the fact that they took longer to complete the trials. The Reach-Grasp segment in movement 3 (the farthest Reach in this task) was the only one where every TR user's Peak Hand Velocity was within two standard deviations of the normative mean. However, they also tended to have high between-trial standard deviations in this segment (except for participant P50).

Table 4.7: End Effector Metrics (Hand Distance Travelled, Hand Trajectory Variability, Number of Movement Units, and Peak Hand Velocity) for the TR BP prosthesis users during each Reach-Grasp (R-G) and Transport-Release (T-RL) segment of the Cup Transfer Task. Standard deviations are shown in brackets (between-participant SD for normative data, and between-trial SD for prosthesis users). Highlighted cells indicate prosthesis user outcomes which were more than two SD from the normative mean: red = higher value than normative, blue = lower.

			Norm	P66	P14	P85	P50	P94
Hand Distance Travelled (mm)	M 1	R-G	366 (52)	332 (25)	459 (135)	385 (37)	650 (82)	338 (25)
		T-RL	646 (39)	641 (29)	671 (25)	688 (19)	713 (10)	655 (19)
	M 2	R-G	456 (56)	456 (28)	529 (31)	443 (36)	561 (129)	515 (14)
		T-RL	700 (46)	704 (21)	670 (18)	729 (28)	763 (52)	727 (21)
	M 3	R-G	887 (35)	896 (22)	1018 (68)	961 (65)	1146 (47)	881 (27)
		T-RL	724 (46)	761 (17)	717 (31)	713 (24)	707 (16)	683 (27)
	M 4	R-G	428 (49)	513 (18)	561 (26)	432 (18)	592 (113)	538 (14)
		T-RL	657 (46)	643 (36)	687 (44)	677 (36)	695 (32)	655 (21)
Hand Trajectory Variability (mm)	M 1	R-G	16 (3)	18	41	22	47	26
		T-RL	17 (4)	22	37	30	51	42
	M 2	R-G	17 (4)	14	22	21	52	40
		T-RL	20 (5)	45	25	47	44	43
	M 3	R-G	26 (5)	28	39	56	47	39
		T-RL	20 (4)	24	21	33	35	58
	M 4	R-G	14 (4)	31	46	20	77	36
		T-RL	20 (4)	31	36	42	54	49
Number of Movement Units	M 1	R-G	1 (0)	5 (1)	4 (1)	6 (2)	13 (3)	9 (2)
		T-RL	2 (0)	5 (2)	6 (2)	6 (2)	13 (2)	10 (2)
	M 2	R-G	1 (0)	2 (1)	3 (1)	5 (2)	7 (2)	9 (3)
		T-RL	2 (0)	3 (1)	4 (1)	4 (2)	12 (3)	9 (2)
	M 3	R-G	2 (0)	3 (1)	3 (1)	6 (1)	6 (1)	6 (2)
		T-RL	2 (1)	3 (1)	3 (1)	5 (2)	12 (2)	8 (2)
	M 4	R-G	1 (0)	5 (3)	6 (2)	6 (2)	11 (2)	9 (2)
		T-RL	2 (0)	4 (1)	5 (1)	8 (2)	19 (4)	8 (2)
Peak Hand Velocity (mm/s)	M 1	R-G	866 (166)	481 (43)	680 (89)	604 (54)	910 (128)	538 (63)
		T-RL	1042 (88)	813 (59)	874 (117)	847 (68)	652 (46)	628 (60)
	M 2	R-G	1149 (139)	884 (72)	753 (20)	838 (99)	685 (154)	603 (81)
		T-RL	940 (70)	786 (51)	803 (67)	899 (65)	730 (48)	698 (56)
	M 3	R-G	1492 (187)	1253 (83)	1486 (235)	1416 (205)	1450 (51)	1408 (132)
		T-RL	1009 (56)	797 (66)	923 (58)	1033 (73)	736 (63)	729 (76)
	M 4	R-G	1157 (147)	909 (93)	915 (107)	869 (72)	799 (158)	874 (59)
		T-RL	979 (76)	853 (69)	852 (74)	783 (60)	594 (75)	697 (55)

When looking at Percent to Peak Hand Velocity, Percent to Peak Hand Deceleration, and Percent to Peak Grip Aperture in the Reach-Grasp movement segments (Table 4.8), these movement features all tended to appear earlier in Reach-Grasp when compared with able-bodied individuals (although Percent to Peak Hand Velocities were still mostly within the normative range, the trend was still present). This shift may have been related to the TR users' tendency to have disproportionately prolonged Grasp phases, which would be consistent with the fact that P14's 'Percent to Peak' metrics did not follow this trend as P14 was the only TR user who did not disproportionately prolong Grasp phases in this task. Also of note was P66, whose outcomes for Percent to Peak Grip Aperture were within the normative range for Reach-Grasp 2, 3 and 4 despite their Peak Hand Deceleration being much earlier. From visual inspection of Figure 4.3b, it appears that P66 tended to plateau with their grip aperture during Reach-Grasp 2 and 3, but that they first reached peak grip aperture at roughly the start of the Grasp phase, while in movement 4 they appeared to move their terminal device close enough to the cup to trigger the start of the Grasp phase, and then open their hook to peak grip aperture. This behaviour of P66 in movement 4 was unusual. Based on visual inspection of the Grip Aperture profiles (Figure 4.3) and the coordinated shift in Percent to Peak Hand Velocity, Hand Deceleration and Grip Aperture (Table 4.8), it appears that the TR BP users were mostly able to coordinate opening of their terminal device with their reaching movement in this task, much like able-bodied individuals (Figure 4.3a). Percent to Peak Grip Aperture was not coupled with Percent to Peak Hand Deceleration for any of the TR BP users, but this was also true for the able-bodied individuals in the normative data set in this task.

Table 4.8: Percent to Peak Hand Velocity, Hand Deceleration and Grip Aperture metrics for the TR BP prosthesis users during each Reach-Grasp (R-G) segment of the Cup Transfer Task. Standard deviations are shown in brackets (between-participant SD for normative data, and between-trial SD for prosthesis users). Highlighted cells indicate prosthesis user outcomes which were more than two SD from the normative mean: red = higher value than normative, blue = lower.

		Norm	P66	P14	P85	P50	P94
Percent to Peak Hand Velocity (%)	R-G 1	35 (4)	20 (7)	27 (9)	25 (5)	17 (4)	15 (4)
	R-G 2	30 (7)	25 (3)	24 (9)	15 (3)	22 (5)	23 (7)
	R-G 3	36 (8)	31 (2)	32 (4)	21 (4)	26 (2)	24 (2)
	R-G 4	25 (5)	21 (5)	22 (6)	17 (3)	28 (8)	21 (3)
Percent to Peak Hand Deceleration (%)	R-G 1	62 (9)	41 (6)	49 (9)	32 (5)	28 (8)	22 (8)
	R-G 2	50 (6)	32 (5)	41 (18)	19 (3)	29 (8)	34 (8)
	R-G 3	61 (5)	47 (5)	52 (12)	31 (6)	36 (7)	30 (2)
	R-G 4	62 (14)	32 (5)	43 (12)	28 (6)	33 (7)	32 (5)
Percent to Peak Grip Aperture (%)	R-G 1	80 (5)	61 (5)	77 (15)	53 (2)	– [1] –	57 (19)
	R-G 2	73 (6)	70 (6)	78 (10)	– [2] –	– –	56 (9)
	R-G 3	80 (4)	79 (10)	82 (6)	51 (12)	56 (20)	56 (11)
	R-G 4	84 (5)	76 (14)	82 (12)	– –	61 (24)	62 (11)

[1] The markers on P50's split-hook were not tracking reliably in the first two movements of the Cup Transfer Task, grip aperture related outcomes for these movements were disregarded.
[2] P85 did not close their hook in between movements 1 and 2 or 3 and 4 (when they did not have to return to home in between movements). This caused our calculation of Percent to Peak Grip Aperture to be unreliable for movements 2 and 4.

With respect to Percent to Peak Hand Velocity in the Transport-Release movement segments (Table 4.9), most were within two standard deviations of the normative mean, and there was not a clear trend in behaviour. This may be related to the fact that the TR BP users had multiple movement units in these segments, and the peak velocity may sometimes be detected in an earlier movement unit and sometimes in a later one.

Table 4.9: Percent to Peak Hand Velocity for the TR BP prosthesis users during each Transport-Release (T-RL) segment of the Cup Transfer Task. Standard deviations are shown in brackets (between-participant SD for normative data, and between-trial SD for prosthesis users). Highlighted cells indicate prosthesis user outcomes which were more than two SD from the normative mean: red = higher value than normative, blue = lower.

		Norm	P66	P14	P85	P50	P94
Percent to Peak Hand Velocity (%)	T-RL 1	21 (3)	25 (3)	25 (3)	22 (3)	16 (4)	25 (6)
	T-RL 2	38 (9)	42 (6)	35 (5)	37 (6)	22 (6)	34 (4)
	T-RL 3	25 (2)	37 (4)	29 (3)	25 (3)	19 (6)	24 (8)
	T-RL 4	28 (8)	43 (6)	36 (4)	37 (4)	25 (4)	37 (6)

4.1.2 Pasta Box Task

Summary visualizations for able-bodied individuals and two of the TR BP users (P66 and P94) for the Pasta Box task are shown in Figure 4.4. As in Figure 4.1 for the Cup Transfer task, the two TR BP users shown in Figure 4.4 represent one of the more skilled users (P66), and one of the less skilled users (P94) for this task. Similar trends can be observed can be observed from Figure 4.4 as were made for the Cup Transfer Task: TR BP users demonstrate longer trial durations, more fixation to Hand in Transport and less smooth movement in Grasp and Release. However, disproportionate prolongation of Grasp is not as clearly observable in this task.

4.1.2.1 Task Performance

Performance metrics of Total Trial Duration and Percent Success Rate for the TR BP prosthesis users on the Pasta Box Task are summarized in Table 4.10. Specific phase durations are shown in Figure 4.5 and relative phase durations are compared in Table 4.11.

Table 4.10: Mean Total Trial Duration and Percent Success Rate for the TR BP prosthesis users performing the Pasta Box Task compared with normative data. Standard deviations for Trial Duration are shown in brackets (between-participant SD for normative data, and between-trial SD for prosthesis users). Highlighted cells indicate prosthesis user outcomes which were more than two SD from the normative mean: red = higher than normative, blue = lower.

	Norm	P66	P14	P85	P50	P94
Trial Duration (s)	8.7 (1.2)	15.1 (2.0)	15.7 (0.9)	17.0 (0.8)	22.6 (1.2)	18.4 (1.1)
Percent Success Rate (%)	96 –	82 –	100 –	90 –	80 –	100 –

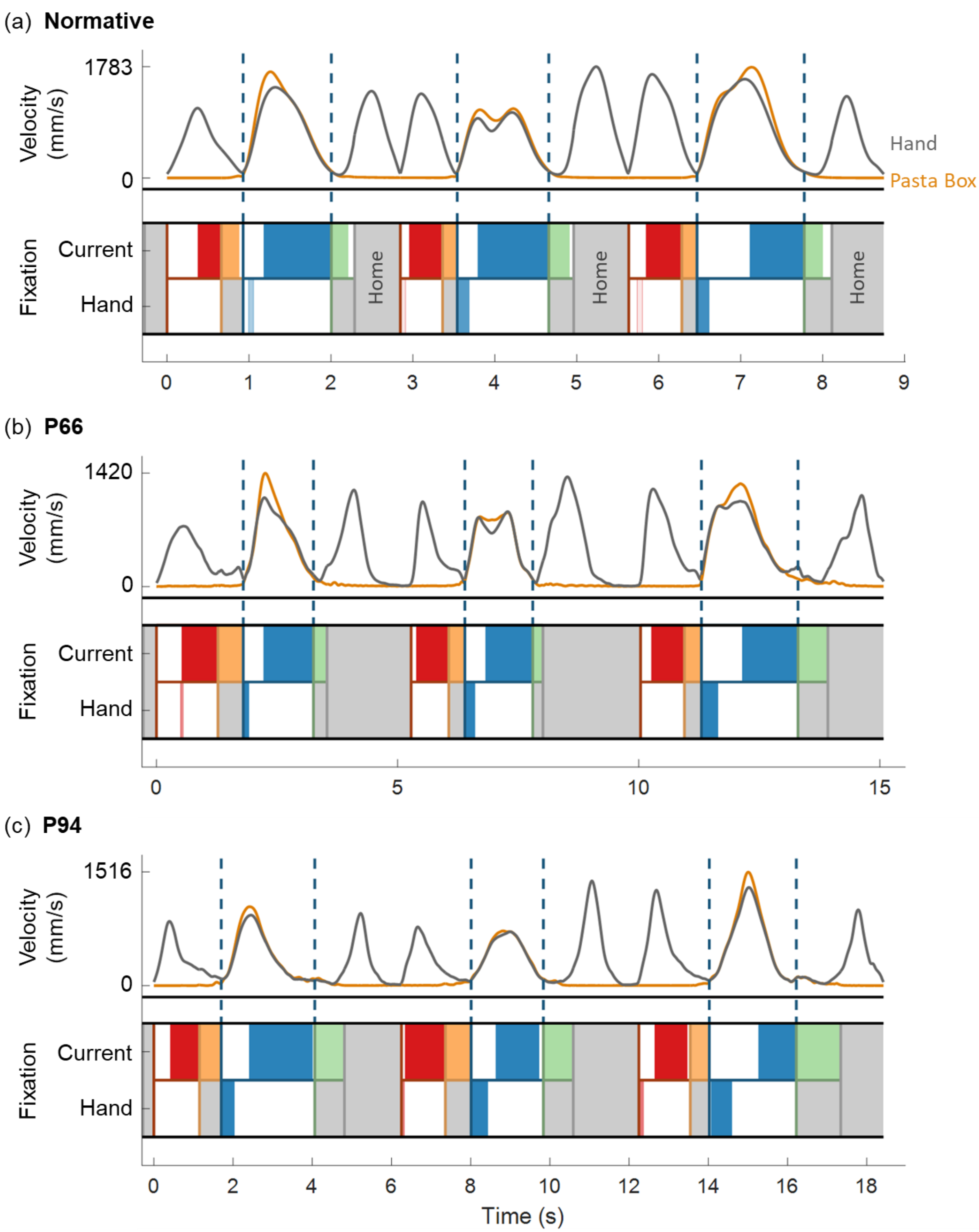

Figure 4.4: Visualizations of average end effector and object velocities as well as eye gaze fixation behaviour for two TR BP prosthesis users performing the Pasta Box Task, compared with normative behaviour: (a) normative data set, (b) P66, (c) P94. Velocity plots are for hand (grey) and pasta box (orange). Fixation plots represent Percent Fixations to 'Current' and 'Hand Only' AOIs throughout each task phase: Reach (red), Grasp (orange), Transport (blue), and Release (green). Opacity level of fixation plots represents probability of fixation. The entire task is plotted with time along the x-axis.

The TR BP prosthesis users took longer than able bodied individuals to perform the Pasta Box Task, and like in the Cup Transfer Task, their Trial Durations were consistently greater than two standard deviations from the normative mean (Table 4.10). However, unlike the Cup Transfer Task, there were fewer participants with disproportionately prolonged Grasp phases in this task. While four of the five participants had exhibited that behaviour in the Cup Transfer Task, only one participant (P85) consistently did this in the Pasta Box Task (see Table 4.11). However, the other four participants' relative phase durations still were not consistent with the normative relative phase durations. The phases in which they spent a disproportionate amount of time varied between Reach, Grasp, and Release (but never Transport). Again, P14 demonstrated the fastest Grasp phases, and was even able to grasp the pasta box as quickly as able-bodied individuals. Also, in contrast to the Cup Transfer Task, grasping quickly did not appear to be associated with an increase in errors on this task, as P14 completed 10 trials of the Pasta Box Task with no errors (Table 4.10).

Table 4.11: Relative Phase Durations for the TR BP prosthesis users performing the Pasta Box Task. Phase durations for the Reach (R), Grasp (G), Transport (T), and Release (RL) phases are expressed as a percentage of the respective movement (R-G-T-RL). Standard deviations are shown in brackets (between-participant SD for normative data, and between-trial SD for prosthesis users). Highlighted cells indicate prosthesis user outcomes which were more than two SD from the normative mean: red = higher value than normative, blue = lower.

Relative Phase Duration (% of movement)							
		Norm	P66	P14	P85	P50	P94
Mvmt 1	R	29 (2)	37 (5)	34 (3)	22 (4)	25 (3)	24 (4)
	G	11 (2)	13 (11)	8 (3)	25 (11)	15 (4)	11 (4)
	T	47 (2)	42 (4)	50 (3)	40 (8)	43 (7)	49 (5)
	RL	12 (2)	8 (5)	8 (3)	13 (4)	17 (8)	16 (1)
Mvmt 2	R	24 (2)	29 (2)	30 (3)	25 (3)	29 (4)	26 (3)
	G	8 (2)	12 (2)	6 (1)	18 (5)	7 (2)	15 (5)
	T	53 (3)	51 (3)	53 (3)	43 (4)	42 (6)	42 (5)
	RL	14 (3)	8 (2)	10 (3)	14 (4)	22 (10)	17 (3)
Mvmt 3	R	26 (2)	24 (4)	35 (4)	28 (5)	32 (8)	26 (2)
	G	7 (2)	9 (3)	4 (1)	15 (6)	10 (7)	9 (3)
	T	53 (2)	51 (10)	48 (5)	43 (6)	38 (5)	43 (6)
	RL	14 (2)	16 (9)	13 (7)	15 (5)	20 (10)	22 (6)

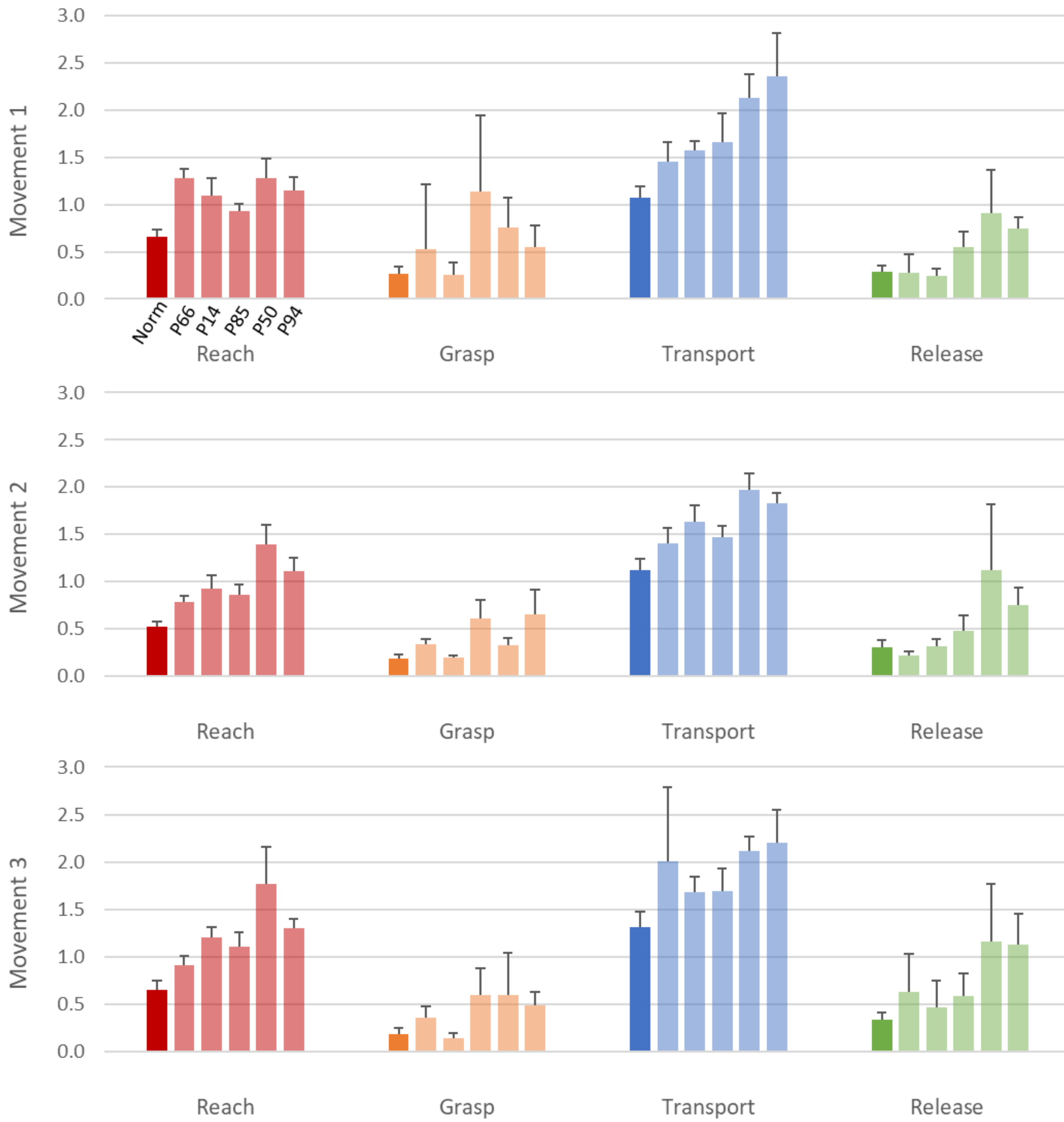

Figure 4.5: Average phase durations for the TR BP prosthesis users (semi-transparent bars, from left to right: P66, P14, P85, P50, P94) performing the Pasta Box Task, compared with normative data (opaque bars).

4.1.2.2 Eye Gaze Fixation

The TR BP prosthesis user's Percent Fixations and Number of Fixations to the Current and Hand Only AOIs during the Reach and Transport phases of the Pasta Box Task are summarized in Table 4.12 and Table 4.13, respectively. Like in the Cup Transfer Task, Percent Fixations during Grasp and Release are not included in this summary because the prosthesis users consistently fixated on the Current pick-up or drop-off target for close to 100% of all Grasp and Release phases (see Table 8 in Appendices B, C, D, E, and F). These outcomes for Percent Fixation to 'Current' during Grasp and Release were usually higher than the normative mean, but still within 2 standard deviations except the last Release phase when participants were placing the pasta box back on the side table. Able-bodied participants tended to fixate on this target less than the targets on the shelves in front of them, while the TR BP prosthesis users still fixated on the pasta box/target for 99 to 100% of this final Release phase. Two of the prosthesis users (P50 and P94) also fixated on this target for a greater percentage of the first reach than the normative population (Table 4.12). Target Locking Strategy was not calculated for the Pasta Box Task, as it did not appear that it would be valid to compare this task to Parr's coin drag and drop task (see Chapter 3, section 3.5.2)

Table 4.12: Mean Percent Fixations for the TR BP prosthesis users to the Current and Hand Only AOIs during the Reach (R) and Transport (T) phases Pasta Box Task. Standard deviations are shown in brackets (between-participant SD for normative data, and between-trial SD for prosthesis users). Highlighted cells indicate prosthesis user outcomes which were more than two SD from the normative mean: red = higher value than normative, blue = lower.

Mean Percent Fixations (When Fixated) (%)								
			Norm	P66	P14	P85	P50	P94
Current AOI	Mvmt 1	R	43 (9)	59 (4)	57 (3)	46 (8)	88 (7)	62 (17)
		T	75 (10)	71 (8)	70 (8)	58 (5)	71 (4)	67 (9)
	Mvmt 2	R	77 (15)	86 (15)	68 (18)	96 (7)	100 (1)	91 (8)
		T	77 (9)	70 (7)	75 (7)	68 (4)	83 (6)	60 (13)
	Mvmt 3	R	66 (16)	76 (15)	74 (12)	90 (15)	96 (4)	63 (16)
		T	50 (5)	54 (11)	50 (4)	46 (5)	57 (5)	42 (8)
Hand Only AOI	Mvmt 1	R	0 (0)	4 (1)	0 (0)	0 (0)	7 (0)	2 (0)
		T	6 (2)	8 (6)	13 (6)	21 (7)	16 (3)	14 (7)
	Mvmt 2	R	11 (9)	0 (0)	0 (0)	0 (0)	0 (0)	7 (4)
		T	13 (7)	15 (10)	13 (4)	19 (7)	12 (5)	22 (11)
	Mvmt 3	R	11 (8)	0 (0)	0 (0)	0 (0)	0 (0)	9 (6)
		T	11 (4)	19 (20)	21 (5)	18 (5)	23 (7)	24 (11)

As in the Cup Transfer Task, the Percent Fixation metrics indicate similar patterns of gaze behaviour between the TR BP prosthesis users in the Pasta Box Task. In addition to consistently fixating on the Current AOI for most of the Grasp and Release phases, the TR BP users tended to follow their end effector with their gaze more than able-bodied individuals as they began to transport the Pasta Box in movements 1 and 3 of this task. This finding was evidenced by higher Percent Fixations to hand during Transport (Table 4.12), Number of Fixations to 'Hand Only' in Transport equalling or exceeding 1 (Table 4.13), and longer ELL_{Pickup} values (see Table 4.14 in section 4.1.2.3). They also followed their end effector with their gaze during Transport 2, but this did not set them apart from normative behaviour, as able-bodied participants also had a slightly higher percent fixation to 'Hand Only' during Transport 2, presumably because the targets were close together and both right in front of the participant, so there was less incentive to transition gaze early. For some of the prosthesis users, this increased fixation to their end effector during Transport corresponded with slightly lower mean percent fixation to the 'Current' AOI, but never enough that it fell below the normative mean minus 2 standard deviations (unlike in the Cup Transfer Task).

Similar to the Cup Transfer Task, the Number of Fixations metric did not indicate that the TR BP participants were employing a strategy of glancing back and forth between their end effector and the 'Current' target during Reach or Transport phases (Table 4.13). It did indicate that three of the prosthesis users (P50, P66 and P94) would glance at their end effector during some Reach phases, which able-bodied individuals almost never do. However, the low mean Number of Fixations in these instances (<1) and high standard deviations indicate that this behaviour was not common in all trials, but generally happened less than half of the time.

Table 4.13: Mean Number of Fixations for the TR BP prosthesis users to the Current and Hand Only AOIs during the Reach (R) and Transport (T) phases Pasta Box Task. Standard deviations are shown in brackets (between-participant SD for normative data, and between-trial SD for prosthesis users). Highlighted cells indicate prosthesis user outcomes which were more than two SD from the normative mean: red = higher value than normative, blue = lower.

Mean Number of Fixations								
			Norm	P66	P14	P85	P50	P94
Current AOI	Mvmt 1	R	1.0 (0.1)	1.0 (0.0)	1.0 (0.0)	1.0 (0.0)	1.0 (0.0)	1.1 (0.3)
		T	1.0 (0.0)	1.0 (0.0)	1.0 (0.0)	1.0 (0.0)	1.1 (0.4)	1.0 (0.0)
	Mvmt 2	R	1.0 (0.0)	1.0 (0.0)	1.0 (0.0)	1.0 (0.0)	1.0 (0.0)	1.2 (0.4)
		T	1.0 (0.1)	1.0 (0.0)	1.0 (0.0)	1.1 (0.3)	1.0 (0.0)	1.9 (0.7)
	Mvmt 3	R	1.0 (0.0)	1.0 (0.0)	1.0 (0.0)	1.2 (0.4)	1.0 (0.0)	1.1 (0.3)
		T	1.1 (0.1)	1.0 (0.0)	1.0 (0.0)	1.0 (0.0)	1.0 (0.0)	1.1 (0.3)
Hand Only AOI	Mvmt 1	R	0.0 (0.0)	0.4 (0.5)	0.0 (0.0)	0.0 (0.0)	0.1 (0.4)	0.1 (0.3)
		T	0.3 (0.3)	1.0 (0.0)	1.0 (0.0)	1.0 (0.0)	1.1 (0.4)	1.0 (0.0)
	Mvmt 2	R	0.0 (0.1)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0	0.5 (0.5)
		T	0.8 (0.3)	1.0 (0.0)	0.9 (0.3)	1.0 (0.0)	1.0 (0.0)	1.0 (0.0)
	Mvmt 3	R	0.1 (0.2)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.6 (0.5)
		T	0.8 (0.3)	1.0 (0.5)	1.1 (0.3)	1.0 (0.0)	1.1 (0.4)	1.0 (0.0)

4.1.2.3 Eye-Hand Latency

Eye-Hand Latency outcomes for the TR BP prosthesis users during the Pasta Box Task are summarized in Table 4.14.

Trends in Eye-Hand Latency metrics were very similar for TR BP prosthesis users between the Cup Transfer and Pasta Box Tasks. Before picking up the pasta box, TR BP participants tended to fixate on it for longer than able-bodied participants, as indicated by greater EAL_{Grasp} and EAL_{Pickup} values. This finding is consistent with their longer phase durations (section 4.1.2.1) and similar or greater Percent Fixations to the 'Current' AOI in Reach (Table 4.12).

Table 4.14: Eye-Hand Latency Metrics for the TR BP prosthesis users during each Movement (M) of the Pasta Box Task: Eye Arrival Latency before Grasp Start (EAL_{Grasp}); Eye Arrival Latency before Transport Start (EAL_{Pickup}); Eye Leaving Latency after Transport Start (ELL_{Pickup}); Eye Arrival Latency before Transport End ($EAL_{Dropoff}$); Eye Leaving Latency after Transport End ($ELL_{Dropoff}$); and Eye Leaving Latency after Release End ($ELL_{Release}$). Standard deviations are shown in brackets (between-participant SD for normative data, and between-trial SD for prosthesis users). Highlighted cells indicate prosthesis user outcomes which were more than two SD from the normative mean: red = higher value than normative, blue = lower.

Mean Eye-Hand Latency Metrics (s)														
			Norm		P66		P14		P85		P50		P94	
Cup Pick-up	EAL_{Grasp}	M 1	0.29	(0.07)	0.75	(0.07)	0.63	(0.13)	0.43	(0.10)	1.13	(0.20)	0.74	(0.24)
		M 2	0.41	(0.11)	0.67	(0.13)	0.64	(0.25)	0.83	(0.12)	1.39	(0.20)	1.02	(0.18)
		M 3	0.44	(0.13)	0.69	(0.13)	0.89	(0.16)	1.03	(0.20)	1.71	(0.42)	0.89	(0.15)
	EAL_{Pickup}	M 1	0.55	(0.11)	1.27	(0.73)	0.88	(0.23)	1.56	(0.81)	1.89	(0.39)	1.29	(0.25)
		M 2	0.58	(0.14)	1.00	(0.17)	0.83	(0.25)	1.43	(0.20)	1.71	(0.22)	1.67	(0.30)
		M 3	0.62	(0.17)	1.04	(0.12)	1.03	(0.18)	1.63	(0.20)	2.31	(0.48)	1.37	(0.21)
	ELL_{Pickup}	M 1	0.02	(0.08)	-0.16	(0.11)	-0.21	(0.09)	-0.35	(0.13)	-0.33	(0.09)	-0.36	(0.15)
		M 2	-0.09	(0.13)	-0.22	(0.16)	-0.18	(0.15)	-0.29	(0.11)	-0.26	(0.12)	-0.52	(0.18)
		M 3	-0.12	(0.09)	-0.32	(0.40)	-0.35	(0.11)	-0.31	(0.11)	-0.53	(0.18)	-0.57	(0.19)
Cup Drop-off	$EAL_{Dropoff}$	M 1	0.82	(0.20)	1.03	(0.18)	1.10	(0.15)	0.97	(0.24)	1.46	(0.34)	1.65	(0.43)
		M 2	0.87	(0.17)	0.98	(0.12)	1.23	(0.21)	1.01	(0.10)	1.63	(0.13)	1.20	(0.20)
		M 3	0.66	(0.10)	1.15	(0.78)	0.84	(0.12)	0.79	(0.20)	1.22	(0.16)	0.96	(0.27)
	$ELL_{Dropoff}$	M 1	-0.30	(0.20)	-0.77	(0.16)	-0.64	(0.19)	-1.27	(0.47)	-1.46	(0.42)	-0.83	(0.51)
		M 2	-0.34	(0.19)	-0.68	(0.17)	-0.59	(0.10)	-1.14	(0.73)	-1.82	(0.67)	-1.00	(0.24)
		M 3	-0.23	(0.09)	-1.11	(0.47)	-1.40	(0.45)	-1.12	(0.44)	-2.34	(0.58)	-1.23	(0.38)
	$ELL_{Release}$	M 1	-0.01	(0.19)	-0.49	(0.08)	-0.39	(0.14)	-0.72	(0.47)	-0.56	(0.45)	-0.08	(0.49)
		M 2	-0.03	(0.17)	-0.47	(0.17)	-0.28	(0.08)	-0.66	(0.61)	-0.69	(0.10)	-0.25	(0.15)
		M 3	0.11	(0.06)	-0.49	(0.39)	-0.95	(0.59)	-0.54	(0.37)	-1.18	(0.71)	-0.10	(0.09)

As was mentioned in section 4.1.2.2, after picking up the pasta box, the TR BP participants tended to remain fixated on it and/or their end effector for longer than able-bodied participants as they started to transport it. This behaviour was associated with longer (more negative) ELL_{Pickup} values, especially in movements 1 and 3.

Before dropping off the pasta box, the prosthesis users' Eye Arrival Latencies ($EAL_{Dropoff}$) also tended to be longer than the normative mean values, although many were less than 2 standard deviations from the normative mean. This result is consistent with the fact that they took longer to transport the box, and fixated on the Current drop-off target for a similar or slightly smaller percentage of the Transport phases (Table 4.12).

After dropping-off the pasta box, the prosthesis users also tended to remain fixated on it even after they had moved their end effector away, as indicated by longer (more negative) Eye Leaving Latencies after Transport and Release end ($ELL_{Dropoff}$ and $ELL_{Release}$). For participants P14 and P50, this behaviour was especially notable after the last Release, when putting the pasta box back on the side table. Interestingly, the TR BP users tended to have longer $ELL_{Release}$ values for the Pasta Box Task than the Cup Transfer Task.

4.1.2.4 End Effector Movement

Hand Distance Travelled, Hand Trajectory Variability, Number of Movement Units, and Peak Hand Velocity are summarized in Table 4.15. Percent to Peak Hand Velocity, Hand Deceleration and Grip Aperture for only the Reach-Grasp movement segments are summarized in Table 4.16, while Percent to Peak Hand Velocity for the Transport-Release segments is presented in Table 4.17.

In the Pasta Box Task, the first Reach-Grasp and last Transport-Release segments (reaching towards or transporting the pasta box to the side table) were consistently associated with increased Hand Distance Travelled and Trajectory Variability in all the TR BP prosthesis users (Table 4.15). In the other movement segments, there was more variability between the TR BP users, with P66 having outcomes which were mostly consistent with the normative values, and the other participants demonstrating increased Hand Distance Travelled and Trajectory Variability, to varying extents. Like in the Cup Transfer Task, P14 and P50 had the most phases in which their Hand Distance Travelled was outside the normative range.

Consistent with the results from the Cup Transfer Task, the TR BP users had higher Numbers of Movement Units per segment than the normative sample (Table 4.15). However, the spread between them was smaller in the Pasta Box Task, with the average Number of Movement Units ranging from 2 to 10. In this task, two users with the lowest Number of Movement Units (P66 and P14) were also the two users with the lowest Percent Fixations to Hand in Transport. However, the trend of higher Number of Movement Units correlating with increased fixations to hand/object in Transport was not as strong in the other three users.

As in the Cup Transfer task, the TR BP prosthesis users' Peak Hand Velocities were generally lower than the normative means. However, in this task, the TR BP users' Peak Hand Velocities were within the normative range more often than in the Cup Transfer Task (Table 4.15).

Table 4.15: End Effector Metrics (Hand Distance Travelled, Hand Trajectory Variability, Number of Movement Units, and Peak Hand Velocity) for the TR BP prosthesis users during each Reach-Grasp (R-G) and Transport-Release (T-RL) segment of the Pasta Box Task. Standard deviations are shown in brackets (between-participant SD for normative data, and between-trial SD for prosthesis users). Highlighted cells indicate prosthesis user outcomes which were more than two SD from the normative mean: red = higher value than normative, blue = lower.

			Norm	P66	P14	P85	P50	P94
Hand Distance Travelled (mm)	M 1	R-G	492 (26)	642 (144)	690 (45)	675 (238)	774 (33)	579 (42)
		T-RL	935 (27)	943 (25)	960 (28)	960 (28)	1032 (80)	966 (46)
	M 2	R-G	505 (23)	498 (9)	585 (26)	474 (32)	567 (35)	543 (44)
		T-RL	802 (61)	861 (22)	1019 (50)	834 (27)	898 (48)	859 (21)
	M 3	R-G	746 (24)	742 (14)	1009 (44)	785 (35)	849 (41)	811 (14)
		T-RL	1186 (31)	1322 (219)	1340 (29)	1719 (57)	1403 (37)	1324 (25)
Hand Trajectory Variability (mm)	M 1	R-G	19 (5)	51	54	48	51	40
		T-RL	22 (4)	49	36	68	75	89
	M 2	R-G	15 (5)	10	25	26	31	43
		T-RL	20 (4)	23	38	32	59	38
	M 3	R-G	19 (4)	15	28	34	51	32
		T-RL	35 (8)	133	80	92	134	69
Number of Movement Units	M 1	R-G	1 (0)	4 (3)	4 (1)	8 (3)	7 (3)	5 (1)
		T-RL	1 (0)	2 (1)	3 (1)	6 (2)	8 (2)	7 (3)
	M 2	R-G	1 (0)	2 (1)	3 (1)	5 (2)	6 (2)	4 (2)
		T-RL	2 (0)	3 (1)	4 (2)	5 (1)	10 (3)	5 (2)
	M 3	R-G	1 (0)	2 (0)	3 (1)	7 (2)	9 (4)	3 (1)
		T-RL	2 (0)	6 (3)	4 (1)	6 (2)	9 (3)	7 (1)
Peak Hand Velocity (mm/s)	M 1	R-G	1164 (163)	827 (96)	1040 (101)	1054 (118)	1299 (148)	916 (66)
		T-RL	1447 (136)	1142 (129)	1103 (108)	1213 (77)	1074 (90)	1073 (127)
	M 2	R-G	1352 (191)	1076 (107)	1223 (148)	976 (102)	924 (76)	896 (106)
		T-RL	1069 (112)	963 (55)	1126 (93)	879 (56)	714 (54)	762 (42)
	M 3	R-G	1666 (261)	1232 (144)	1539 (119)	1276 (203)	1206 (165)	1303 (181)
		T-RL	1598 (180)	1301 (157)	1564 (113)	2113 (169)	1255 (74)	1352 (122)

When examining Percent to Peak Hand Velocity, Hand Deceleration and Grip Aperture in the Reach-Grasp movement segments (Table 4.16), a coordinated shift of these features earlier in the movement was not observable, as it had been in the Cup Transfer Task. For example, P14 reached peak velocity and peak grip aperture at a similar point in the Reach-Grasp motion as able-bodied individuals, but in the first movement (pick-up at the side table) their peak hand deceleration was quite a bit later, and in the other movements it was earlier. Another TR BP user, P50, had Percent to Peak Hand Velocity, Hand Deceleration and Grip Aperture values which were consistently earlier than normative even though they did not have disproportionately prolonged Grasp phases in this task (Table 4.11).

Table 4.16: Percent to Peak Hand Velocity, Hand Deceleration and Grip Aperture metrics for the TR BP prosthesis users during each Reach-Grasp (R-G) segment of the Pasta Box Task. Standard deviations are shown in brackets (between-participant SD for normative data, and between-trial SD for prosthesis users). Highlighted cells indicate prosthesis user outcomes which were more than two SD from the normative mean: red = higher value than normative, blue = lower.

		Norm	P66	P14	P85	P50	P94
Percent to Peak Hand Velocity (%)	R-G 1	41 (4)	30 (6)	35 (9)	20 (5)	19 (4)	24 (4)
	R-G 2	37 (4)	21 (2)	30 (2)	15 (4)	18 (6)	24 (6)
	R-G 3	36 (4)	21 (2)	35 (5)	17 (4)	22 (5)	26 (3)
Percent to Peak Hand Deceleration (%)	R-G 1	56 (8)	86 (22)	75 (17)	37 (18)	34 (13)	34 (5)
	R-G 2	73 (9)	36 (8)	46 (17)	28 (7)	38 (23)	33 (11)
	R-G 3	73 (8)	47 (8)	46 (4)	31 (7)	39 (22)	35 (6)
Percent to Peak Grip Aperture (%)	R-G 1	73 (7)	89 (8)	85 (6)	80 (16)	62 (27)	75 (8)
	R-G 2	80 (8)	81 (7)	74 (10)	73 (14)	58 (30)	64 (10)
	R-G 3	81 (5)	90 (1)	83 (8)	74 (18)	53 (24)	71 (7)

The decreased coordination between movement characteristics shown in Table 4.16 indicates that some of the TR BP participants were less able to coordinate their grip opening and Reach movements in the Pasta Box Task compared with the Cup Transfer Task. This might be because the Pasta Box Task involves object manipulations at locations which are typically more challenging for body-powered prosthesis users (low and to the side, shoulder height and across the body). However, no strong evidence existed that this additional challenge caused increased fixations to their end effector during Reach.

In Transport, Percent to Peak Hand Velocity values (Table 4.17) were mostly within two standard deviations of the normative mean. The less skilled users (P50 and P94) had some Transport phases with earlier peak velocities, which had also been observed with P50 in the Cup Transfer Task.

Table 4.17: Percent to Peak Hand Velocity for the TR BP prosthesis users during each Transport-Release (T-RL) segment of the Pasta Box Task. Standard deviations are shown in brackets (between-participant SD for normative data, and between-trial SD for prosthesis users). Highlighted cells indicate prosthesis user outcomes which were more than two SD from the normative mean: red = higher value than normative, blue = lower.

		Norm	P66	P14	P85	P50	P94
Percent to Peak Hand Velocity (%)	T-RL 1	29 (3)	26 (3)	37 (4)	27 (4)	19 (4)	22 (5)
	T-RL 2	45 (9)	42 (19)	47 (5)	42 (3)	25 (9)	35 (6)
	T-RL 3	36 (4)	31 (8)	38 (5)	35 (3)	36 (9)	30 (3)

4.2 Transhumeral Body-Powered Prosthesis Users

Overall, outcomes for two of the transhumeral (TH) body-powered prosthesis users (P44 and P96) generally overlapped with the TR users, while P03 tended to follow the same trends in behaviour, but was often further from normative than the other TH users. The exception to this was in the outcomes for Percent Fixations, where all three of the TH prosthesis users tended to look at their terminal device slightly more, and to the 'Current' AOI less than the TR users. The outcome metrics for the TH BP prosthesis users will be explored in detail in the following sections.

Detailed reports on the results for each individual prosthesis user are provided in Appendices G (P44), Appendix H (P96), and Appendix I (P03).

4.2.1 Cup Transfer Task

Summary visualizations for able-bodied individuals and two of the TH BP users (P44 and P96) for the Cup Transfer Task are shown in Figure 4.6.

Because eye gaze metrics were not available for P03 for this task, both TH users for whom a complete set of outcome measures was available are represented in Figure 4.6. These visualizations show similar trends for the TH users as those discussed for the TR users (Figure 4.1) in section 4.1.1. However, although the TH users' trial durations are closer to the more skilled TR user shown in Figure 4.1 (P14), their Percent Fixations appear to be more similar to the less skilled TR user (P50), or possibly even more hand-focused, based on these visualizations (greater proportion of blue in the row for fixations to hand).

4.2.1.1 Task Performance

Performance metrics of Total Trial Duration and Percent Success Rate for the TH BP prosthesis users for the Cup Transfer Task are summarized in Table 4.18. Specific phase durations are shown in Figure 4.7 and relative phase durations are compared in Table 4.19.

Table 4.18: Mean Total Trial Duration and Percent Success Rate for the TH BP prosthesis users performing the Cup Transfer Task compared with normative data. Standard deviations for Trial Duration are shown in brackets (between-participant SD for normative data, and between-trial SD for prosthesis users). Highlighted cells indicate prosthesis user outcomes which were more than two SD from the normative mean: red = higher value than normative, blue = lower.

	Norm	P44	P96	P03
Trial Duration (s)	10.5 (1.3)	21.1 (1.1)	18.5 (2.5)	40.1 (2.6)
Percent Success Rate (%)	89 –	83 –	90 –	90 –

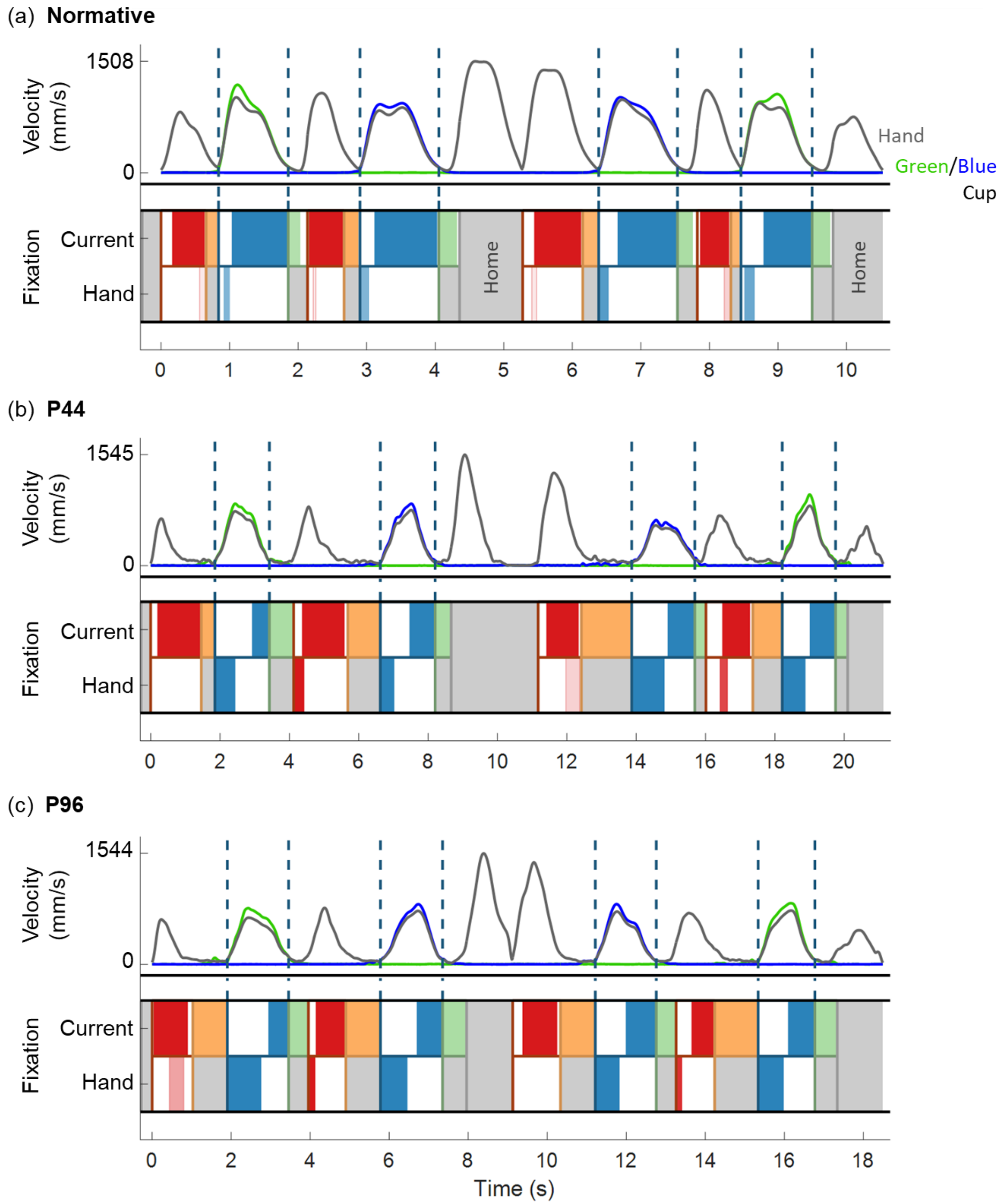

Figure 4.6: Visualizations of average end effector and object velocities as well as eye gaze fixation behaviour for two TH BP prosthesis users performing the Cup Transfer Task, compared with normative behaviour: (a) normative data set, (b) P44, (c) P96. Velocity plots are for hand (grey) and objects (green cup and blue cup). Fixation plots represent Percent Fixations to 'Current' and 'Hand Only' AOIs throughout each task phase: Reach (red), Grasp (orange), Transport (blue), and Release (green). Opacity level of fixation plots represents probability of fixation. The entire task is plotted with time along the x-axis.

Like the TR BP prosthesis users, the TH BP users all took longer than the normative cohort (2-4 times) to complete the Cup Transfer Task. Two of the TH participants (P44 and P96) had total trial times which were similar to the TR participants, while one participant's mean trial duration (P03) was about 10 seconds longer than the slowest TR BP user. Also like the TR users, the TH users tended to have disproportionately prolonged grasp phases in this task, except P44 in movement 1 (Table 4.19).

Table 4.19: Relative Phase Durations for the TH BP prosthesis users performing the Cup Transfer Task. Phase durations for the Reach (R), Grasp (G), Transport (T), and Release (RL) phases are expressed as a percentage of the respective movement (R-G-T-RL). Standard deviations are shown in brackets (between-participant SD for normative data, and between-trial SD for prosthesis users). Highlighted cells indicate prosthesis user outcomes which were more than two SD from the normative mean: red = higher value than normative, blue = lower.

Relative Phase Duration (% of movement)					
		Norm	P44	P96	P03
Mvmt 1	R	31 (2)	35 (5)	26 (3)	22 (4)
	G	8 (2)	10 (2)	22 (4)	19 (5)
	T	48 (2)	38 (5)	39 (4)	31 (3)
	RL	13 (2)	17 (3)	12 (4)	28 (5)
Mvmt 2	R	24 (2)	34 (4)	24 (2)	18 (2)
	G	10 (2)	21 (4)	21 (7)	19 (4)
	T	52 (3)	35 (2)	40 (6)	33 (3)
	RL	14 (3)	10 (3)	15 (2)	30 (3)
Mvmt 3	R	34 (2)	26 (6)	29 (3)	20 (2)
	G	9 (2)	29 (13)	21 (4)	20 (5)
	T	45 (2)	38 (8)	37 (3)	33 (5)
	RL	11 (3)	7 (4)	12 (3)	27 (6)
Mvmt 4	R	25 (3)	33 (4)	24 (4)	23 (2)
	G	7 (2)	20 (9)	26 (7)	19 (7)
	T	53 (3)	38 (5)	35 (4)	28 (3)
	RL	15 (4)	9 (3)	14 (3)	30 (5)

4.2.1.2 Eye Gaze Fixation

P03's gaze calibration for the Cup Transfer Task was unreliable, so observations on eye gaze-related metrics for this task are based only on P44 and P96. Like the TR users, these two TH users tended to fixate on the 'Current' AOI for 100% or close to 100% of Grasp and Release (see Table 4 in Appendices G, H, and I). Percent Fixations and Number of Fixations to the Current and Hand Only AOIs during the Reach and Transport phases of the Pasta Box Task are summarized in Table 4.20 and Table 4.21. Target Locking Strategy (Parr et al. 2017) for the Reach phases, is presented in Table 4.22.

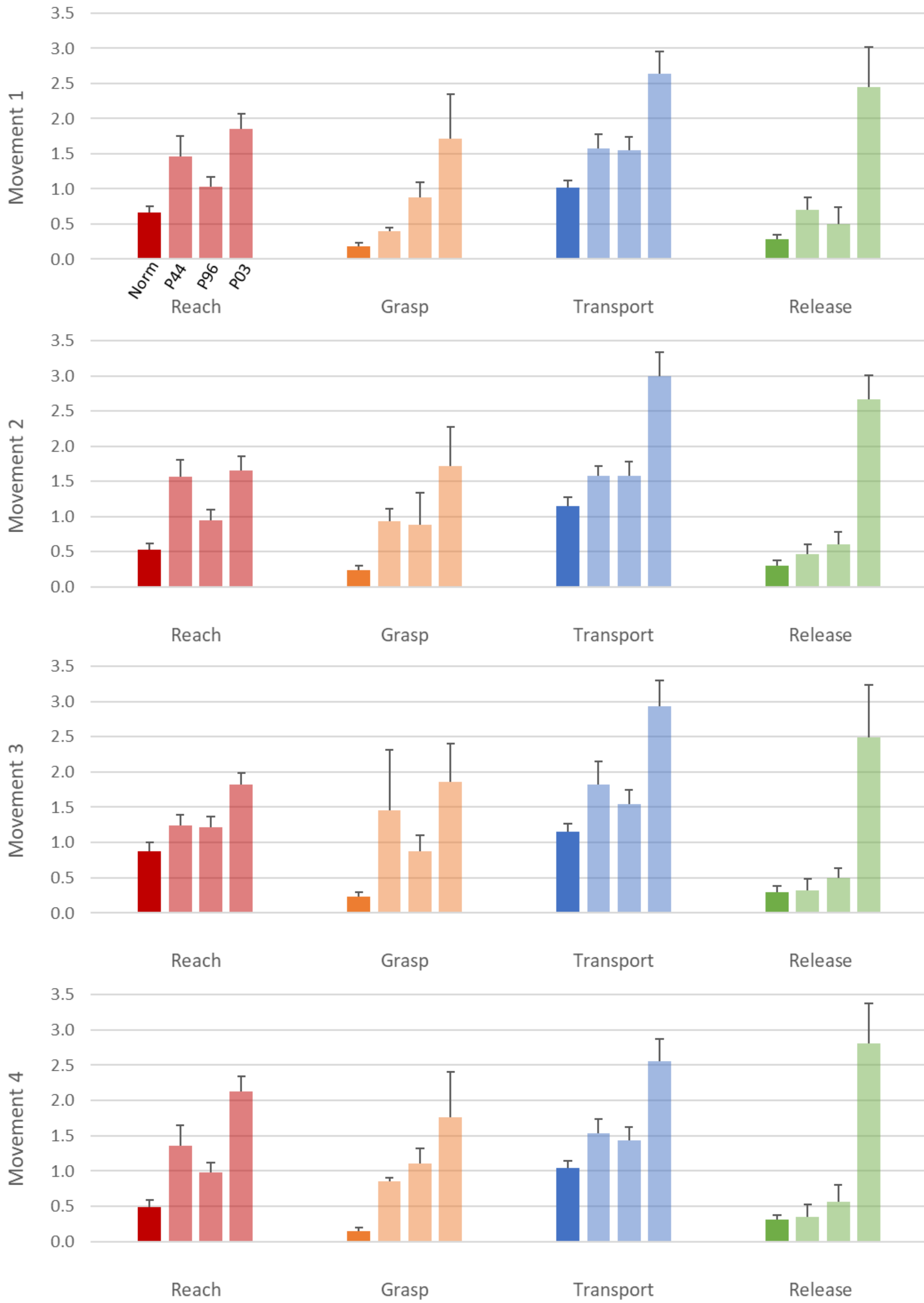

Figure 4.7: Average phase durations for the TH BP prosthesis users (semi-transparent bars, from left to right: P44, P96, P03) performing the Cup Transfer Task, compared with normative data (opaque bars).

The two TH prosthesis user participants showed similar trends in gaze behaviour as the TR users, but they tended to have more phases where their Percent Fixation outcomes were outside of the normative range (of ± 2 SD). The TH users' Percent Fixations to Hand Only during Transport were greater than the normative range in every Transport phase (Table 4.20). In addition, in three of the four Transport phases, both P44 and P96 had lower than normal Percent Fixations to the drop-off target. This behaviour (reduced fixation to 'Current' in Transport) was only observed in two of the TR users, and only in two of their Transport phases. Furthermore, the TH users tended to have more Reach phases with fixations to 'Hand Only,' and higher Percent Fixation to Hand Only when fixated in Reach.

Table 4.20: Mean Percent Fixations of the TH BP prosthesis users to the Current and Hand Only AOIs during the Reach (R) and Transport (T) phases Cup Transfer Task. Standard deviations are shown in brackets (between-participant SD for normative data, and between-trial SD for prosthesis users). Highlighted cells indicate prosthesis user outcomes which were more than two SD from the normative mean: red = higher value than normative, blue = lower.

Mean Percent Fixations (When Fixated) (%)					
			Norm	P44	P96
Current AOI	Mvmt 1	R	72 (15)	86 (5)	85 (17)
		T	79 (11)	31 (5)	33 (8)
	Mvmt 2	R	93 (7)	79 (13)	81 (9)
		T	80 (12)	47 (7)	41 (3)
	Mvmt 3	R	78 (15)	75 (10)	72 (10)
		T	74 (11)	45 (17)	50 (7)
	Mvmt 4	R	85 (12)	59 (5)	60 (7)
		T	66 (15)	48 (3)	47 (2)
Hand Only AOI	Mvmt 1	R	14 (7)	0 (0)	31 (6)
		T	8 (5)	36 (17)	54 (14)
	Mvmt 2	R	8 (4)	19 (12)	18 (8)
		T	10 (4)	25 (16)	43 (7)
	Mvmt 3	R	7 (5)	33 (0)	3 (3)
		T	12 (6)	49 (18)	39 (8)
	Mvmt 4	R	17 (12)	17 (10)	15 (6)
		T	14 (10)	43 (9)	45 (6)

Like the TR prosthesis users, Number of Fixations did not imply a strategy of glancing back and forth between end effector and drop-off target during Transport, as increases in Number of Fixations to those targets did not correspond (Table 4.21). Instead, it appeared that the BP prosthesis users would generally follow their hand at the beginning of Transport and then transition their gaze to the drop-off target once they were confident enough, but not glance back and forth. However, for P96, there were corresponding increases in Number of Fixations to 'Current' and 'Hand Only' in the Reach phases of movements 1 and 3, indicating that in some trials they would look at the pick-up target, then at their end effector and then back to the pick-up target during Reach.

Table 4.21: Mean Number of Fixations of the TH BP prosthesis users to the Current and Hand Only AOIs during the Reach (R) and Transport (T) phases Cup Transfer Task. Standard deviations are shown in brackets (between-participant SD for normative data, and between-trial SD for prosthesis users). Highlighted cells indicate prosthesis user outcomes which were more than two SD from the normative mean: red = higher value than normative, blue = lower.

Mean Number of Fixations					
			Norm	P44	P96
Current AOI	Mvmt 1	R	1.0 (0.1)	1.0 (0.0)	1.3 (0.5)
		T	1.0 (0.0)	1.0 (0.0)	1.0 (0.0)
	Mvmt 2	R	1.0 (0.0)	1.0 (0.0)	1.0 (0.0)
		T	1.0 (0.0)	1.0 (0.0)	1.0 (0.0)
	Mvmt 3	R	1.0 (0.1)	1.0 (0.0)	1.6 (0.5)
		T	1.0 (0.0)	1.0 (0.0)	1.0 (0.0)
	Mvmt 4	R	1.0 (0.1)	1.2 (0.4)	1.0 (0.0)
		T	1.0 (0.1)	1.0 (0.0)	1.0 (0.0)
Hand Only AOI	Mvmt 1	R	0.0 (0.0)	0.0 (0.0)	0.3 (0.5)
		T	0.5 (0.3)	1.4 (0.9)	1.8 (0.7)
	Mvmt 2	R	0.1 (0.1)	1.2 (0.4)	1.0 (0.0)
		T	0.6 (0.3)	1.2 (0.4)	1.0 (0.0)
	Mvmt 3	R	0.1 (0.2)	0.2 (0.4)	0.6 (0.5)
		T	0.7 (0.3)	1.2 (0.4)	1.9 (0.3)
	Mvmt 4	R	0.1 (0.2)	0.8 (0.8)	0.9 (0.3)
		T	0.7 (0.4)	1.2 (0.4)	1.4 (0.5)

The TH BP users' outcomes for TLS during Reach were mostly within the normative range, except in movement 2 (Table 4.22), like the TR users (Table 4.5). However, their TLS values did tend to be lower than the TR users', and in movement 4 were close to the value of 40% which Parr et al. (2017) had observed for individuals using a simulated transradial myoelectric prosthesis.

Table 4.22: Mean Target Locking Strategy (TLS) outcomes (calculated as Percent Fixation to Current – Percent Fixation to Hand Only, as per Parr et al. 2017) for the TH BP prosthesis users during the Reach phases of the Cup Transfer Task. Standard deviations are shown in brackets (between-participant SD for normative data, and between-trial SD for prosthesis users). Highlighted cells indicate prosthesis user outcomes which were more than two SD from the normative mean: red = higher value than normative, blue = lower.

Mean Target Locking Strategy (%)			
	Norm	P44	P96
Reach 1	69 (18)	86 (5)	75 (31)
Reach 2	92 (9)	61 (25)	63 (16)
Reach 3	76 (17)	68 (23)	70 (10)
Reach 4	81 (21)	49 (15)	47 (9)

4.2.1.3 Eye-Hand Latency

Eye-Hand Latency outcomes for the TH BP prosthesis users during the Cup Transfer Task are summarized in Table 4.23.

Table 4.23: Eye-Hand Latency Metrics for the TH BP prosthesis users during each Movement (M) of the Cup Transfer Task: Eye Arrival Latency before Grasp Start (EAL_{Grasp}); Eye Arrival Latency before Transport Start (EAL_{Pickup}); Eye Leaving Latency after Transport Start (ELL_{Pickup}); Eye Arrival Latency before Transport End ($EAL_{Dropoff}$); Eye Leaving Latency after Transport End ($ELL_{Dropoff}$); and Eye Leaving Latency after Release End ($ELL_{Release}$). Standard deviations are shown in brackets (between-participant SD for normative data, and between-trial SD for prosthesis users). Highlighted cells indicate prosthesis user outcomes which were more than two SD from the normative mean: red = higher value than normative, blue = lower.

Mean Eye-Hand Latency Metrics (s)								
			Norm		P44		P96	
Cup Pick-up	EAL_{Grasp}	M 1	0.48	(0.14)	1.27	(0.32)	0.73	(0.29)
		M 2	0.50	(0.10)	1.01	(0.57)	0.76	(0.10)
		M 3	0.70	(0.15)	0.78	(0.45)	0.96	(0.19)
		M 4	0.42	(0.09)	0.53	(0.44)	0.59	(0.08)
	EAL_{Pickup}	M 1	0.66	(0.16)	1.66	(0.35)	1.60	(0.34)
		M 2	0.73	(0.16)	1.95	(0.64)	1.64	(0.53)
		M 3	0.93	(0.19)	2.23	(0.95)	1.84	(0.22)
		M 4	0.57	(0.10)	1.38	(0.79)	1.68	(0.42)
	ELL_{Pickup}	M 1	-0.02	(0.10)	-0.55	(0.34)	-1.02	(0.27)
		M 2	-0.04	(0.10)	-0.38	(0.26)	-0.68	(0.19)
		M 3	-0.06	(0.18)	-0.95	(0.50)	-0.54	(0.23)
		M 4	-0.06	(0.19)	-0.68	(0.18)	-0.58	(0.21)
Cup Drop-off	$EAL_{Dropoff}$	M 1	0.82	(0.15)	0.49	(0.08)	0.50	(0.10)
		M 2	0.94	(0.12)	0.74	(0.08)	0.65	(0.09)
		M 3	0.87	(0.16)	0.78	(0.19)	0.77	(0.14)
		M 4	0.70	(0.17)	0.74	(0.05)	0.68	(0.09)
	$ELL_{Dropoff}$	M 1	-0.15	(0.10)	-0.93	(0.34)	-0.67	(0.28)
		M 2	-0.32	(0.26)	-0.61	(0.23)	-0.78	(0.20)
		M 3	-0.22	(0.11)	-0.56	(0.22)	-0.68	(0.21)
		M 4	-0.34	(0.19)	-0.62	(0.13)	-1.17	(0.41)
	$ELL_{Release}$	M 1	0.14	(0.09)	-0.23	(0.24)	-0.16	(0.09)
		M 2	-0.02	(0.25)	-0.15	(0.10)	-0.17	(0.09)
		M 3	0.06	(0.11)	-0.24	(0.11)	-0.18	(0.12)
		M 4	-0.04	(0.17)	-0.27	(0.05)	-0.60	(0.33)

Overall trends in Eye-Hand Latency outcomes were similar between the TR and TH prosthesis users, except when examining EAL_{Grasp} and $EAL_{Dropoff}$.

When picking up the cup before the start of Transport, the TH BP prosthesis users' Eye Arrival Latencies (EAL_{Pickup}) were consistently longer than the normative mean plus two standard deviations, like the TR users. However, their EAL_{Grasp} values were within the normative range in at least half of the movements (not prolonged despite their prolonged Reach phases). This finding is mostly likely related to them glancing at their terminal device in some Reach phases (section 4.2.1.2). After picking up the cup, the TH users' Eye Leaving Latencies (ELL_{Pickup}) were longer than the normative cohort's and similar to the values observed in some of the TR users.

Before droping-off of the cup at the target location, the TH users' $EAL_{Dropoff}$ values were similar to or lower than the normative mean. This sets them apart from TR users, whose $EAL_{Dropoff}$ values were consistently on par with or greater than the normative values (Table 4.6). After dropping off the cup, $ELL_{Dropoff}$ and $ELL_{Release}$ values were consistently negative and longer than normative, although still within two standard deviations for some phases. This behaviour was consistent with the behaviour observed in some of the TR users (P14 and P50 in particular).

4.2.1.4 End Effector Movement

The end effector metrics of Hand Distance Travelled, Hand Trajectory Variability, Number of Movement Units, and Peak Hand Velocity are summarized in Table 4.24. Percent to Peak Hand Velocity, Hand Deceleration and Grip Aperture for only the Reach-Grasp segments of each movement are summarized together in Table 4.25, while Percent to Peak Hand Velocity for the Transport-Release segments is presented in Table 4.26.

Relative to the normative data set, the TH BP prosthesis users demonstrated similar trends in end effector metrics as the TR users. Their outcomes for Hand Distance Travelled were similar to the normative mean or greater, like the TR users. However, the TR users never exceeded the normative range in Transport-Release segments in this task (Table 4.7), whereas P03 and P44 each had at least one Transport-Release segment where their Hand Distance Travelled was more than two standard deviations from normative (Table 4.24). Also, like the TR users, the TH users had greater Hand Trajectory Variability and Number of Movement units than normative, while their Peak Hand Velocities were generally lower. For P44 and P96, the magnitudes of these outcomes were within the range observed in the TR users, but P03 generally had higher Numbers of Movement Units and lower Peak Hand Velocities than the other BP prosthesis users.

Table 4.24: End Effector Metrics (Hand Distance Travelled, Hand Trajectory Variability, Number of Movement Units, and Peak Hand Velocity) for the TH BP prosthesis users during each Reach-Grasp (R-G) and Transport-Release (T-RL) segment of the Cup Transfer Task. Standard deviations are shown in brackets (between-participant SD for normative data, and between-trial SD for prosthesis users). Highlighted cells indicate prosthesis user outcomes which were more than two SD from the normative mean: red = higher value than normative, blue = lower.

			Norm		P44		P96		P03	
Hand Distance Travelled (mm)	M 1	R-G	366	(52)	373	(38)	350	(33)	358	(21)
		T-RL	646	(39)	748	(36)	663	(19)	754	(48)
	M 2	R-G	456	(56)	574	(16)	468	(50)	488	(34)
		T-RL	700	(46)	701	(7)	694	(21)	727	(40)
	M 3	R-G	887	(35)	1055	(72)	1018	(50)	919	(67)
		T-RL	724	(46)	653	(15)	661	(16)	722	(27)
	M 4	R-G	428	(49)	556	(59)	567	(28)	613	(42)
		T-RL	657	(46)	680	(18)	667	(15)	766	(49)
Hand Trajectory Variability (mm)	M 1	R-G	16	(3)	26		18		23	
		T-RL	17	(4)	40		26		40	
	M 2	R-G	17	(4)	35		27		36	
		T-RL	20	(5)	34		29		52	
	M 3	R-G	26	(5)	105		83		56	
		T-RL	20	(4)	53		24		44	
	M 4	R-G	14	(4)	50		41		46	
		T-RL	20	(4)	27		25		35	
Number of Movement Units	M 1	R-G	1	(0)	6	(1)	6	(1)	16	(4)
		T-RL	2	(0)	6	(3)	5	(2)	21	(4)
	M 2	R-G	1	(0)	8	(1)	4	(2)	12	(4)
		T-RL	2	(0)	4	(1)	4	(1)	22	(3)
	M 3	R-G	2	(0)	8	(4)	4	(1)	14	(4)
		T-RL	2	(1)	4	(2)	4	(1)	23	(6)
	M 4	R-G	1	(0)	7	(3)	8	(2)	15	(3)
		T-RL	2	(0)	4	(1)	4	(2)	23	(4)
Peak Hand Velocity (mm/s)	M 1	R-G	866	(166)	713	(76)	645	(67)	415	(75)
		T-RL	1042	(88)	793	(100)	686	(88)	539	(66)
	M 2	R-G	1149	(139)	957	(169)	850	(71)	458	(32)
		T-RL	940	(70)	794	(82)	781	(66)	524	(74)
	M 3	R-G	1492	(187)	1505	(108)	1546	(119)	1088	(127)
		T-RL	1009	(56)	702	(100)	750	(38)	508	(66)
	M 4	R-G	1157	(147)	833	(159)	811	(59)	611	(136)
		T-RL	979	(76)	852	(66)	795	(66)	617	(61)

From looking at Table 4.25 and the Grip Aperture profiles (Figure 4.8) it appears that the TH users were mostly able to coordinate their grip opening and reaching in this task, similar to the TR users (see section 4.1.1.4). One exception was P96 in Reach-Grasp 4, who appeared to display a similar behaviour as P66 in that movement (not widening their grip aperture until they had moved within the Grasp distance threshold).

Table 4.25: Percent to Peak Hand Velocity, Hand Deceleration and Grip Aperture metrics for the TH BP prosthesis users during each Reach-Grasp (R-G) segment of the Cup Transfer Task. Standard deviations are shown in brackets (between-participant SD for normative data, and between-trial SD for prosthesis users). Highlighted cells indicate prosthesis user outcomes which were more than two SD from the normative mean: red = higher value than normative, blue = lower.

		Norm	P44	P96	P03
Percent to Peak Hand Velocity (%)	R-G 1	35 (4)	17 (3)	14 (3)	19 (3)
	R-G 2	30 (7)	19 (4)	23 (3)	24 (6)
	R-G 3	36 (8)	20 (6)	27 (5)	17 (3)
	R-G 4	25 (5)	22 (7)	17 (7)	22 (6)
Percent to Peak Hand Deceleration (%)	R-G 1	62 (9)	27 (5)	27 (6)	22 (3)
	R-G 2	50 (6)	23 (4)	35 (11)	25 (13)
	R-G 3	61 (5)	30 (8)	36 (8)	24 (8)
	R-G 4	62 (14)	33 (9)	32 (13)	31 (6)
Percent to Peak Grip Aperture (%)	R-G 1	80 (5)	– [1] –	56 (12)	55 (11)
	R-G 2	73 (6)	– –	80 (15)	77 (20)
	R-G 3	80 (4)	– –	68 (6)	56 (9)
	R-G 4	84 (5)	– –	92 (13)	62 (16)

[1] The markers on P44's split-hook were not tracking reliably in the Cup Transfer Task, grip aperture related outcomes were disregarded.

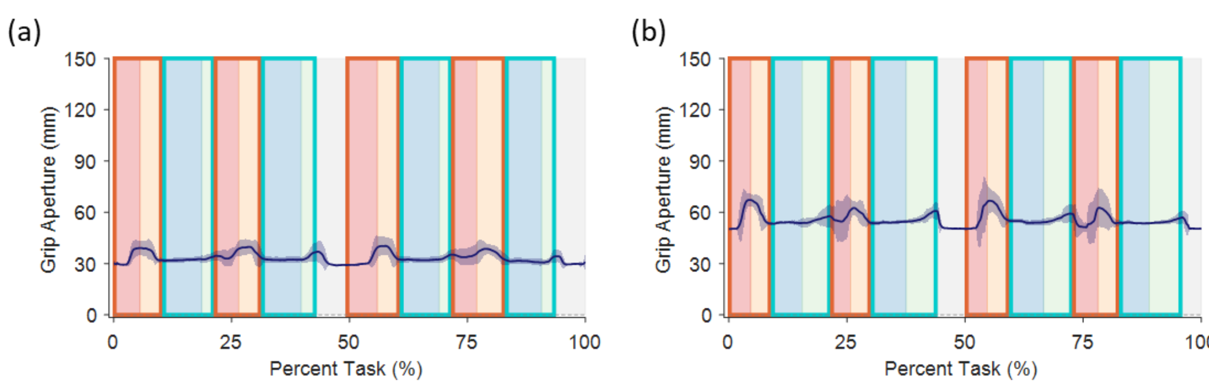

Figure 4.8: Grip Aperture profiles for the TH BP prosthesis users while performing the Cup Transfer Task: (a) P96, (b) P03. Shading shows ± one standard deviation. Task phases are shown: Reach (red), Grasp (orange), Transport (blue), and Release (green). The grip aperture profile for P44 is not shown, as the markers on their split-hook terminal device were not tracking reliably. The grip aperture profile for the normative data set is shown in Figure 4.3.

In Transport, the TH users' Percent to Peak Hand Velocities (Table 4.26) were similar to normative or later, but never earlier, as had been observed in the less skilled TR users.

Table 4.26: Percent to Peak Hand Velocity for the TH BP prosthesis users during each Transport-Release (T-RL) segment of the Cup Transfer Task. Standard deviations are shown in brackets (between-participant SD for normative data, and between-trial SD for prosthesis users). Highlighted cells indicate prosthesis user outcomes which were more than two SD from the normative mean: red = higher value than normative, blue = lower.

		Norm	P44	P96	P03
Percent to Peak Hand Velocity (%)	T-RL 1	21 (3)	28 (6)	26 (5)	23 (3)
	T-RL 2	38 (9)	44 (7)	45 (4)	26 (5)
	T-RL 3	25 (2)	41 (10)	28 (3)	21 (5)
	T-RL 4	28 (8)	44 (3)	40 (5)	23 (2)

4.2.2 Pasta Box Task

Summary visualizations for able-bodied individuals and two of the TH BP users (P96 and P03) for the Pasta Box Task are shown in Figure 4.9. These visualizations reveal that the Pasta Box Task may have been especially challenging for the TH users. In particular, their end effector velocity profiles for this task appear to be far less smooth than the TR users (Figure 4.4) or the TH users on the Cup Transfer Task (Figure 4.6).

4.2.2.1 Task Performance

Performance metrics of Total Trial Duration and Percent Success Rate for the TH BP prosthesis users for the Pasta Box Task are summarized in Table 4.27. Phase durations are shown in Figure 4.10 and relative phase durations are compared in Table 4.28.

Table 4.27: Mean Total Trial Duration and Percent Success Rate for the TH BP prosthesis users performing the Pasta Box Task compared with normative data. Standard deviations for Trial Duration are shown in brackets (between-participant SD for normative data, and between-trial SD for prosthesis users). Highlighted cells indicate prosthesis user outcomes which were more than two SD from the normative mean: red = higher value than normative, blue = lower.

	Norm	P44	P96	P03
Trial Duration (s)	8.7 (1.2)	21.6 (0.8)	19.7 (3.0)	29.3 (2.2)
Percent Success Rate (%)	96 –	56 –	73 –	80 –

In the Pasta Box Task, the TH users had total trial durations which were consistently longer than the normative cohort. As in the Cup Transfer Task, two of the TH users' (P44 and P96) mean trial durations were within the range observed in the five TR users, while P03 took longer to complete the task.

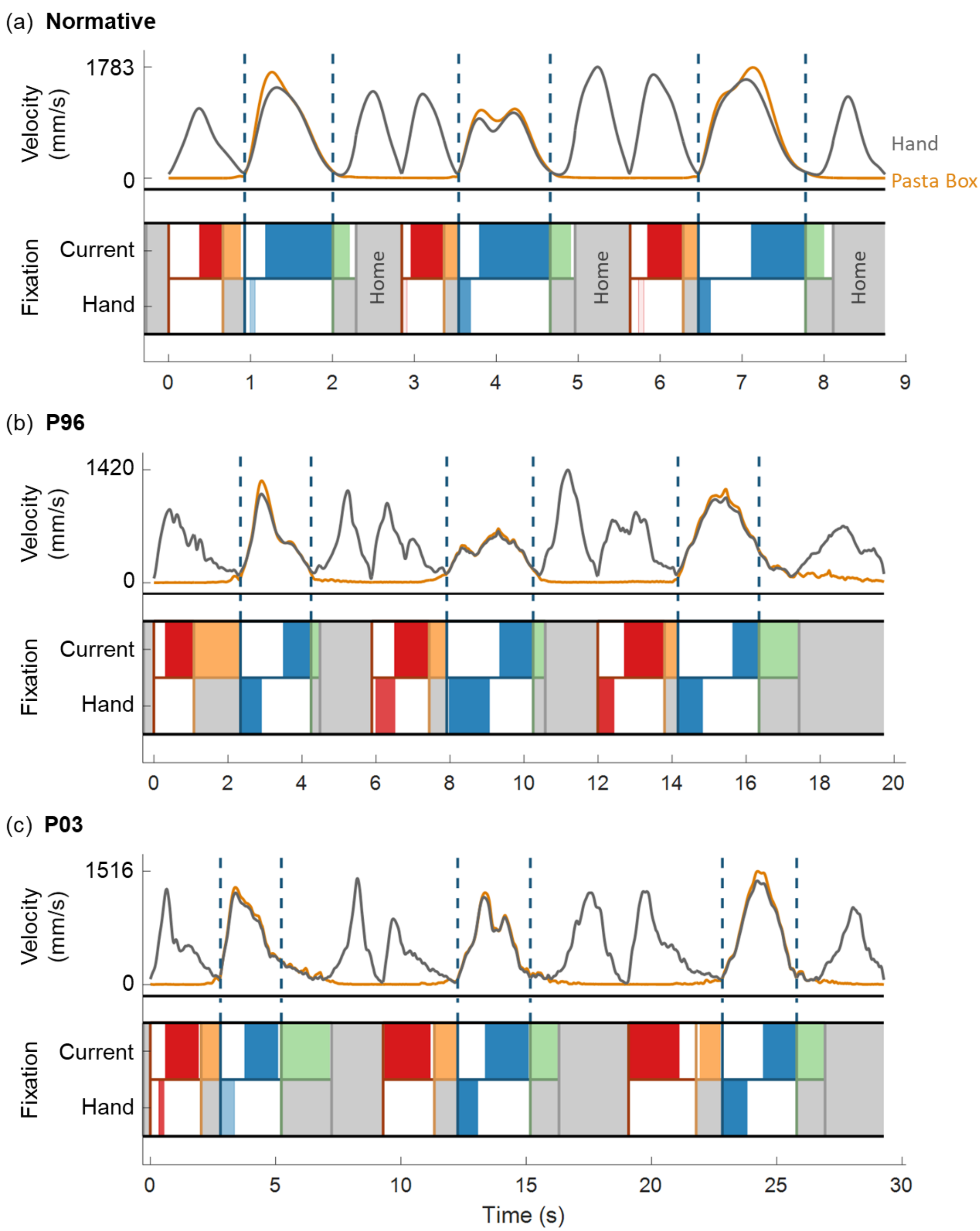

Figure 4.9: Visualizations of average end effector and object velocities as well as eye gaze fixation behaviour for two TH BP prosthesis users performing the Pasta Box Task, compared with normative behaviour: (a) normative data set, (b) P96, (c) P03. Velocity plots are for hand (grey) and pasta box (orange). Fixation plots represent Percent Fixations to 'Current' and 'Hand Only' AOIs throughout each task phase: Reach (red), Grasp (orange), Transport (blue), and Release (green). Opacity level of fixation plots represents probability of fixation. The entire task is plotted with time along the x-axis.

With respect to relative phase durations, each of the three TH users spent a disproportionate amount of time in the Reach phases of movements 2 and 3 (reaching for the pasta box on the shelves). Aside from this trend, there was variability between the TH users: P03 spent a disproportionate amount of time in the first Release phase, while P96 was able to complete Release 1 and 2 very quickly but took a disproportionate amount of time in Grasp 1 and Release 3 (at the side table), and P44 was fast in Release 2 and 3 (Table 4.28).

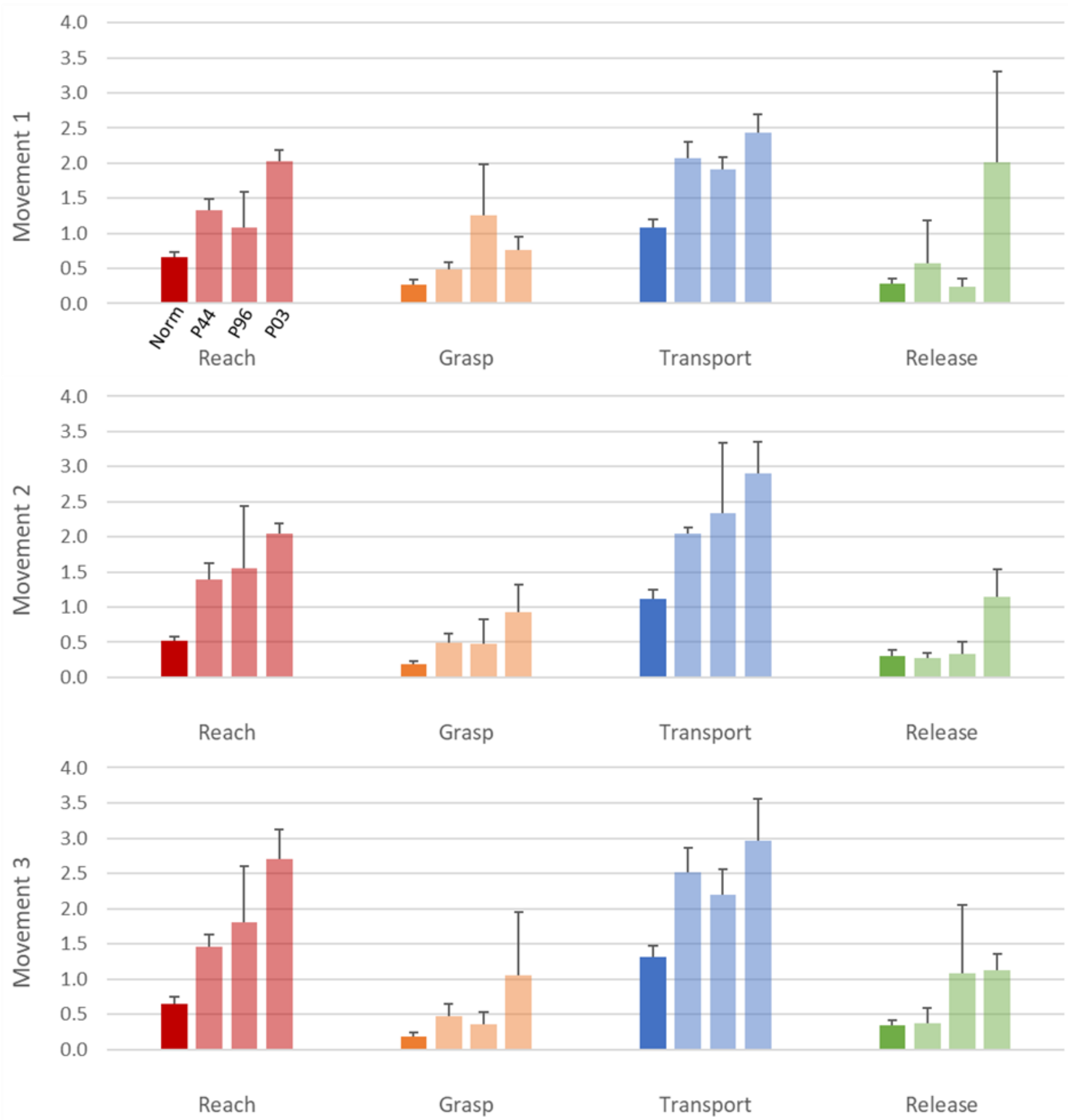

Figure 4.10: Average phase durations for the TH BP prosthesis users (semi-transparent bars, from left to right: P44, P96, P03) performing the Pasta Box Task, compared with normative data (opaque bars).

Table 4.28: Relative Phase Durations for the TH BP prosthesis users performing the Pasta Box Task. Phase durations for the Reach (R), Grasp (G), Transport (T), and Release (RL) phases are expressed as a percentage of the respective movement (R-G-T-RL). Standard deviations are shown in brackets (between-participant SD for normative data, and between-trial SD for prosthesis users). Highlighted cells indicate prosthesis user outcomes which were more than two SD from the normative mean: red = higher value than normative, blue = lower.

Relative Phase Duration (% of movement)					
		Norm	P44	P96	P03
Mvmt 1	R	29 (2)	30 (4)	24 (9)	29 (4)
	G	11 (2)	11 (3)	27 (12)	11 (4)
	T	47 (2)	47 (9)	44 (6)	34 (7)
	RL	12 (2)	12 (12)	5 (2)	26 (14)
Mvmt 2	R	24 (2)	33 (5)	34 (17)	30 (4)
	G	8 (2)	12 (3)	10 (5)	13 (4)
	T	53 (3)	49 (5)	50 (13)	41 (4)
	RL	14 (3)	6 (2)	7 (3)	16 (4)
Mvmt 3	R	26 (2)	30 (4)	33 (13)	35 (6)
	G	7 (2)	10 (4)	7 (3)	12 (7)
	T	53 (2)	52 (3)	42 (12)	38 (6)
	RL	14 (2)	7 (4)	18 (15)	15 (3)

4.2.2.2 Eye Gaze Fixation

The TH BP prosthesis users' Percent Fixations and Number of Fixations to the Current and Hand Only AOIs during the Reach and Transport phases of the Pasta Box Task are summarized in Table 4.27, Table 4.29 and Table 4.30, respectively. Percent Fixations to the 'Current' AOI during Grasp and Release were consistently close to 100% and are not included in the tables (see Table 8 in Appendices G, H, and I).

Like the TR users, The TH BP prosthesis users tended to fixate on their terminal device or the object they were transporting for a greater percentage of Transport 1 and 3 than normative in the Pasta Box Task (Table 4.29). As in the Cup Transfer Task, the TH users' Percent Fixations to Hand Only during Transport were generally higher than for the TR users. The difference between the TR users and TH users appeared to be more pronounced in the Pasta Box Task, as most of the TH user values for mean Percent Fixation to Hand in Transport were greater than the highest value from the TR users (of 24%, for P94 in movement 3). In addition, each of the TH users had at least one Transport phase where their Percent Fixation to the drop-off target was below the normative range (whereas this never occurred for the TR users in this task).

All three of the TH users had a higher than normal Percent Fixation to the pick-up target during Reach 1 (Table 4.29), a behaviour which had also been observed in two of the TR users (P50 and P94).

Table 4.29: Mean Percent Fixations of the TH BP prosthesis users to the Current and Hand Only AOIs during the Reach (R) and Transport (T) phases Pasta Box Task. Standard deviations are shown in brackets (between-participant SD for normative data, and between-trial SD for prosthesis users). Highlighted cells indicate prosthesis user outcomes which were more than two SD from the normative mean: red = higher value than normative, blue = lower.

Mean Percent Fixations (When Fixated) (%)						
			Norm	P44	P96	P03
Current AOI	Mvmt 1	R	43 (9)	78 (4)	67 (15)	66 (7)
		T	75 (10)	49 (2)	40 (7)	55 (10)
	Mvmt 2	R	77 (15)	90 (10)	71 (24)	89 (13)
		T	77 (9)	60 (2)	43 (11)	60 (9)
	Mvmt 3	R	66 (16)	98 (4)	64 (16)	73 (14)
		T	50 (5)	37 (5)	32 (7)	46 (5)
Hand Only AOI	Mvmt 1	R	0 (0)	10 (7)	0 (0)	10 (4)
		T	6 (2)	26 (5)	30 (8)	21 (11)
	Mvmt 2	R	11 (9)	10 (0)	23 (16)	0 (0)
		T	13 (7)	14 (5)	43 (15)	27 (10)
	Mvmt 3	R	11 (8)	0 (0)	20 (13)	0 (0)
		T	11 (4)	40 (17)	30 (13)	32 (15)

Table 4.30: Mean Number of Fixations of the TH BP prosthesis users to the Current and Hand Only AOIs during the Reach (R) and Transport (T) phases Cup Transfer Task. Standard deviations are shown in brackets (between-participant SD for normative data, and between-trial SD for prosthesis users). Highlighted cells indicate prosthesis user outcomes which were more than two SD from the normative mean: red = higher value than normative, blue = lower.

Mean Number of Fixations						
			Norm	P44	P96	P03
Current AOI	Mvmt 1	R	1.0 (0.1)	1.0 (0.0)	1.0 (0.0)	1.6 (0.5)
		T	1.0 (0.0)	1.3 (0.6)	1.0 (0.0)	1.4 (0.5)
	Mvmt 2	R	1.0 (0.0)	1.0 (0.0)	1.0 (0.0)	1.5 (0.5)
		T	1.0 (0.1)	1.0 (0.0)	1.0 (0.0)	1.3 (0.5)
	Mvmt 3	R	1.0 (0.0)	1.0 (0.0)	1.0 (0.0)	2.6 (1.1)
		T	1.1 (0.1)	1.0 (0.0)	1.0 (0.0)	1.0 (0.0)
Hand Only AOI	Mvmt 1	R	0.0 (0.0)	0.7 (0.6)	0.0 (0.0)	0.8 (0.5)
		T	0.3 (0.3)	1.0 (0.0)	2.1 (0.4)	0.5 (0.5)
	Mvmt 2	R	0.0 (0.1)	0.3 (0.6)	0.8 (0.9)	0.0 (0.0)
		T	0.8 (0.3)	1.0 (0.0)	1.6 (0.5)	1.5 (0.8)
	Mvmt 3	R	0.1 (0.2)	0.0 (0.0)	0.9 (0.6)	0.0 (0.0)
		T	0.8 (0.3)	1.7 (1.2)	1.8 (0.7)	1.3 (0.7)

Patterns in the outcomes for Number of Fixations did not indicate that the TH users were employing a strategy of glancing back and forth between their end effector and the drop-off target during Transport (Table 4.30). However, P03 did have elevated Number of Fixations to 'Current' in a number of phases that generally did not correspond with increased Number of Fixations to Hand Only. Looking at the time series data revealed that this was often caused by gaps in the eye data which were too long to be filled under our rules for filling gaps (longer than 100 ms) or jittery movement in the gaze vector. As in the Cup Transfer Task, Number of Fixations did indicate that the TH users would glance at their end effector during Reach in some trials, but these glances were quite brief, as their Percent Fixations to Hand Only in Reach never exceeded the normative range in this task.

4.2.2.3 Eye-Hand Latency

Eye-Hand Latency outcomes for the TH BP prosthesis users during the Pasta Box Task are summarized in Table 4.31.

Table 4.31: Eye-Hand Latency Metrics for the TH BP prosthesis users during each Movement (M) of the Cup Transfer Task: Eye Arrival Latency before Grasp Start (EAL_{Grasp}); Eye Arrival Latency before Transport Start (EAL_{Pickup}); Eye Leaving Latency after Transport Start (ELL_{Pickup}); Eye Arrival Latency before Transport End ($EAL_{Dropoff}$); Eye Leaving Latency after Transport End ($ELL_{Dropoff}$); and Eye Leaving Latency after Release End ($ELL_{Release}$). Standard deviations are shown in brackets (between-participant SD for normative data, and between-trial SD for prosthesis users). Highlighted cells indicate prosthesis user outcomes which were more than two SD from the normative mean: red = higher value than normative, blue = lower.

Mean Eye-Hand Latency Metrics (s)										
			Norm		P44		P96		P03	
Cup Pick-up	EAL_{Grasp}	M 1	0.29	(0.07)	1.03	(0.10)	0.77	(0.51)	1.44	(0.21)
		M 2	0.41	(0.11)	1.24	(0.29)	0.94	(0.38)	1.98	(0.14)
		M 3	0.44	(0.13)	1.41	(0.15)	1.09	(0.42)	2.63	(0.46)
	EAL_{Pickup}	M 1	0.55	(0.11)	1.51	(0.01)	2.03	(0.78)	2.20	(0.26)
		M 2	0.58	(0.14)	1.74	(0.22)	1.41	(0.23)	2.91	(0.44)
		M 3	0.62	(0.17)	1.89	(0.21)	1.45	(0.49)	3.68	(1.04)
	ELL_{Pickup}	M 1	0.02	(0.08)	-0.53	(0.06)	-1.15	(0.19)	-0.52	(0.23)
		M 2	-0.09	(0.13)	-0.30	(0.10)	-1.31	(1.09)	-0.92	(0.36)
		M 3	-0.12	(0.09)	-0.97	(0.68)	-0.79	(0.39)	-1.03	(0.56)
Cup Drop-off	$EAL_{Dropoff}$	M 1	0.82	(0.20)	1.09	(0.27)	0.75	(0.12)	1.47	(0.17)
		M 2	0.87	(0.17)	1.23	(0.04)	0.91	(0.12)	1.70	(0.48)
		M 3	0.66	(0.10)	0.92	(0.08)	0.72	(0.28)	1.34	(0.25)
	$ELL_{Dropoff}$	M 1	-0.30	(0.20)	-1.13	(0.42)	-0.84	(0.20)	-2.80	(1.37)
		M 2	-0.34	(0.19)	-1.01	(0.18)	-0.76	(0.22)	-1.81	(0.55)
		M 3	-0.23	(0.09)	-2.02	(0.63)	-2.59	(1.35)	-2.05	(0.50)
	$ELL_{Release}$	M 1	-0.01	(0.19)	-0.56	(0.64)	-0.60	(0.21)	-0.80	(0.38)
		M 2	-0.03	(0.17)	-0.74	(0.13)	-0.44	(0.14)	-0.66	(0.42)
		M 3	0.11	(0.06)	-1.65	(0.78)	-1.51	(1.68)	-0.92	(0.48)

Eye-Hand Latency outcomes for the TH BP prosthesis users followed similar trends for the Pasta Box Task as the Cup Transfer Task, except when looking at $EAL_{Dropoff}$. In the Cup Transfer Task, the TH users' $EAL_{Dropoff}$ values had been consistently similar to or even shorter than normative values. In this task, P96 followed this trend, but P03 and P44 had $EAL_{Dropoff}$ values which were longer than for the normative cohort. Additionally, in a similar trend as the TR prosthesis users, the TH users' outcomes for $ELL_{Release}$ were generally larger for this task than the Cup Transfer Task.

4.2.2.4 End Effector Movement

Hand Distance Travelled, Hand Trajectory Variability, Number of Movement Units, and Peak Hand Velocity for the TH BP prosthesis users during the Pasta Box Task are summarized in Table 4.32. Percent to Peak Hand Velocity, Hand Deceleration and Grip Aperture for only the Reach-Grasp movement segments are summarized in Table 4.33, while Percent to Peak Hand Velocity for the Transport-Release segments is presented in Table 4.34.

Table 4.32: End Effector Metrics (Hand Distance Travelled, Hand Trajectory Variability, Number of Movement Units, and Peak Hand Velocity) for the TH BP prosthesis users during each Reach-Grasp (R-G) and Transport-Release (T-RL) segment of the Pasta Box Task. Standard deviations are shown in brackets (between-participant SD for normative data, and between-trial SD for prosthesis users). Highlighted cells indicate prosthesis user outcomes which were more than two SD from the normative mean: red = higher value than normative, blue = lower.

			Norm		P44		P96		P03	
Hand Distance Travelled (mm)	M 1	R-G	492	(26)	611	(29)	937	(492)	730	(53)
		T-RL	935	(27)	1102	(210)	960	(32)	1142	(85)
	M 2	R-G	505	(23)	555	(51)	803	(321)	555	(25)
		T-RL	802	(61)	746	(22)	846	(174)	1036	(110)
	M 3	R-G	746	(24)	850	(75)	940	(299)	950	(61)
		T-RL	1186	(31)	1371	(65)	1468	(212)	1340	(54)
Hand Trajectory Variability (mm)	M 1	R-G	19	(5)	16		85		29	
		T-RL	22	(4)	109		56		152	
	M 2	R-G	15	(5)	31		97		27	
		T-RL	20	(4)	36		79		42	
	M 3	R-G	19	(4)	35		135		70	
		T-RL	35	(8)	61		202		99	
Number of Movement Units	M 1	R-G	1	(0)	6	(1)	7	(3)	8	(1)
		T-RL	1	(0)	5	(2)	4	(1)	15	(6)
	M 2	R-G	1	(0)	6	(20	6	(3)	12	(2)
		T-RL	2	(0)	6	(2)	7	(5)	11	(3)
	M 3	R-G	1	(0)	5	(2)	7	(4)	16	(6)
		T-RL	2	(0)	6	(1)	8	(4)	12	(2)
Peak Hand Velocity (mm/s)	M 1	R-G	1164	(163)	869	(133)	985	(238)	783	(121)
		T-RL	1447	(136)	990	(43)	1016	(88)	993	(102)
	M 2	R-G	1352	(191)	1014	(148)	1118	(104)	544	(50)
		T-RL	1069	(112)	622	(42)	604	(41)	696	(124)
	M 3	R-G	1666	(261)	1360	(50)	1224	(232)	875	(128)
		T-RL	1598	(180)	1070	(67)	1228	(248)	876	(76)

With respect to end effector metrics, the TH BP prosthesis users mostly resembled the less skilled TR users in the Pasta Box Task, as they had for the Cup Transfer Task. As per the Cup Transfer Task, the main exception was P03 who had higher mean Number of Movement Units than the TR users in all phases, and generally had lower Peak Hand Velocities. It is interesting that P96's Numbers of Movement Units were not notably larger than those observed in the TR users (specifically P85, P50 and P94) as P96's end effector velocity profile did appear less smooth than the TR users, and they appeared to have more movement units in Reach and Transport phases (Figure 4.9 and Figure 4.4).

The TH BP users did not consistently prolong Grasp phases in the Pasta Box Task (section 4.2.2.1); however, their Peak Hand Velocities and Peak Hand Deceleration did tend to appear earlier in Reach-Grasp phases (Table 4.33). From looking at Percent to Peak Grip Aperture and grip aperture profiles (Figure 4.11), it appeared that P03 was reaching peak grip aperture before initiating Grasp and then plateauing, while P96 was reaching peak grip aperture at the start of Grasp in movement 2 and 3 (even though their peak hand deceleration was quite early in these phases), but only widening their grip after the Grasp start in movement 1. In each of these cases, there exists a lack of coordination between hand velocity, grip aperture, and transition from Reaching into Grasping.

Table 4.33: Percent to Peak Hand Velocity, Hand Deceleration and Grip Aperture metrics for the TH BP prosthesis users during each Reach-Grasp (R-G) segment of the Pasta Box Task. Standard deviations are shown in brackets (between-participant SD for normative data, and between-trial SD for prosthesis users). Highlighted cells indicate prosthesis user outcomes which were more than two SD from the normative mean: red = higher value than normative, blue = lower.

		Norm	P44	P96	P03
Percent to Peak Hand Velocity (%)	R-G 1	41 (4)	20 (2)	30 (11)	24 (2)
	R-G 2	37 (4)	18 (2)	26 (16)	17 (5)
	R-G 3	36 (4)	20 (3)	37 (17)	19 (4)
Percent to Peak Hand Deceleration (%)	R-G 1	56 (8)	41 (15)	44 (24)	28 (3)
	R-G 2	73 (9)	33 (5)	34 (10)	30 (8)
	R-G 3	73 (8)	35 (7)	34 (22)	37 (18)
Percent to Peak Grip Aperture (%)	R-G 1	73 (7)	– [1] –	71 (30)	75 (8)
	R-G 2	80 (8)	– –	67 (30)	59 (9)
	R-G 3	81 (5)	– –	72 (30)	68 (14)

[1] The markers on P44's split-hook were not tracking reliably in the Pasta Box Task, grip aperture related outcomes were disregarded.

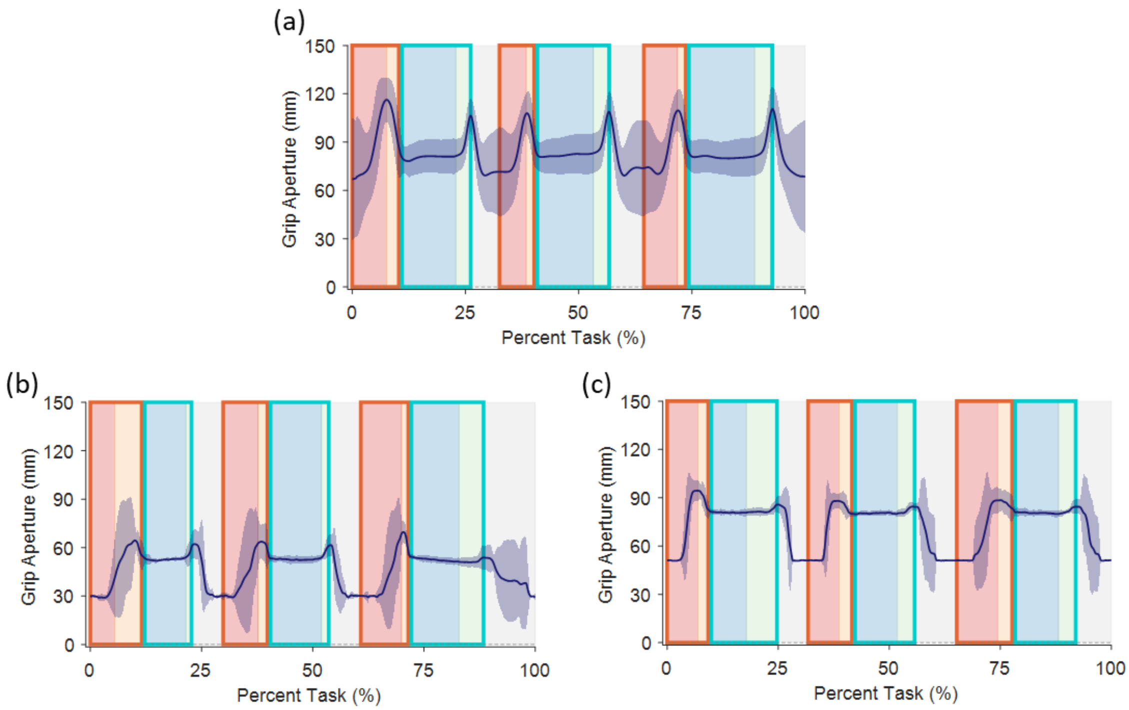

Figure 4.11: Grip Aperture profiles for the TH BP prosthesis users while performing the Pasta Box compared with normative data: (a) normative data set, (b) P96, (c) P03. Shading shows ± one standard deviation (between-participant SD for normative data, and between-trial SD for prosthesis users). Task phases are shown: Reach (red), Grasp (orange), Transport (blue), and Release (green). The grip aperture profile for P44 is not shown, as the markers on their split-hook terminal device were not tracking reliably.

With respect to Percent to Peak Hand Velocity in Transport (Table 4.34), P44 tended to reach peak velocity with their terminal device later than able-bodied individuals, while P96 tended to be similar, and P03 earlier, especially in the first transport from the side-table to the first shelf.

Table 4.34: Percent to Peak Hand Velocity for the TH BP prosthesis users during each Transport-Release (T-RL) segment of the Pasta Box Task. Standard deviations are shown in brackets (between-participant SD for normative data, and between-trial SD for prosthesis users). Highlighted cells indicate prosthesis user outcomes which were more than two SD from the normative mean: red = higher value than normative, blue = lower.

		Norm	P44	P96	P03
Percent to Peak Hand Velocity (%)	T-RL 1	29 (3)	59 (34)	27 (4)	21 (10)
	T-RL 2	45 (9)	52 (5)	48 (14)	28 (2)
	T-RL 3	36 (4)	53 (3)	40 (10)	33 (9)

Chapter 5. Discussion

5.1 Summary of Visuomotor Behaviour for Transradial Body-Powered Prosthesis Users

The main trends which characterized all five of the transradial (TR) body-powered (BP) users' visuomotor behaviour relative to able-bodied individuals were: longer task completion times, increased fixations to their terminal device and objects being manipulated, and less smooth end effector movement. There was, however, some variability in behaviour between the TR BP prosthesis users, which generally corresponded to their skill level and revealed differences in strategies used to accomplish the tasks.

The TR users consistently took longer than able-bodied individuals to complete both the Cup Transfer and Pasta Box Task. This was not a surprising result, as it has been shown that prosthesis users take longer to perform timed assessment tasks such as the Box and Blocks Test (Hebert & Lewicke 2012; Haverkate et al. 2016). However, these outcomes have only focused on overall task duration, and not examined timing of specific movements throughout the task. Our results showed that this prolongation is generally not proportional across all phases of a task. Instead, the TR BP users tended to spend a disproportionate amount of time in particular task phases. In the Pasta Box Task, participants varied with respect to what movement phases were disproportionately prolonged. The only phase which participants never spent a disproportionate time in was Transport. When interacting with the bead-filled compliant cups in the Cup Transfer Task, the majority of the prosthesis users spent a disproportionate amount of time in the Grasp phases. Only one participant (P14) did not follow this trend, demonstrating Grasp phase durations which were almost as brief as for able-bodied individuals. This participant was rated as the second most skilled of the TR users based on the AM-ULA scores, and demonstrated this skill throughout the tasks based on their speed and relatively low Percent Fixations to their terminal device. However, this user also showed less precision in grip aperture, whereas users with prolonged Grasp had less overshoot in grip aperture when grasping and releasing the cups. This indicates a difference in priorities between the TR users when it comes to grasping speed versus precision.

The TR BP prosthesis users also fixated more on their terminal device and the object they were manipulating than able-bodied individuals, especially when transporting an object. This was most notable in the Cup Transfer Task, where users had 2 to 4 times the percentage fixation compared to the normative cohort. This likely indicates decreased confidence in the reliability of their grasp, as they continued to fixate on their hand during Transport, and it may have taken them longer to build up enough confidence to make a saccade to the drop-off target. However, even though the TR users continued to fixate on their hand at the start of Transport, they would still transition their gaze early enough so that their fixation to the drop-off target during Transport was mostly within the normative range, and the amount of lead time between their eye gaze and terminal device arriving at the drop-off target was on par with able-bodied individuals or greater. The only participants whose percentage fixation to the drop-off target fell below normative were P50 and P66 in the Cup Transfer Task. P50 was rated as one of the least skilled TR BP users on both the AM-ULA and UEFS, and their increased reliance on visual feedback is consistent with these results. However, P66 was rated as one of the most skilled users based on the AM-ULA and their outcome metrics were some of the closest to normative when looking at trial/phase durations and end effector metrics in both tasks, as well as eye gaze fixation metrics in the Pasta Box Task. This is an indication that the Cup Transfer Task challenged P66 in ways that the Pasta Box Task did not, and which were only detected by examining eye gaze behaviour. It is interesting to note that in the Cup Transfer Task the two most skilled TR BP users (P66 and P14) each appeared to make sacrifices in at least one aspect of behaviour, as P14 demonstrated decreased movement precision in grip aperture and P66 demonstrated increased visual attention to their prosthesis.

It is also interesting to note that the while the eye gaze behaviour of the TR BP prosthesis users was most different from normative in the Transport phases of the tasks, Transport was the only phase that was never disproportionately prolonged by the TR users (i.e. the Transport phase relative phase durations were consistently similar to or less than normative, while Reach, Grasp, or Release were disproportionately prolonged). Bouwsema et al. (2010) suggested that increased reliance on visual feedback may cause slower movement because it is processed more slowly than visual attention. Our results do not dispute this hypothesis, as the TR users did fixate on their prosthesis/the object they were manipulating for nearly 100% of Grasp and Release phases, which were often greatly prolonged. However, our results also indicate that while transporting an object, prosthesis users may use visual feedback differently; as a compensation that gives them the confidence to move quickly in order to minimize the time when the object is at risk of being dropped.

It has been suggested that some prosthesis users might employ a strategy of glancing back and forth between their terminal device and the current target of their action (Bouwsema et al. 2012; Sobuh et al. 2014). In the five TR BP prosthesis users in this study we did not see any evidence of this behaviour during the Transport phases of the tasks, likely due to the use of a voluntary opening hook that would ensure relatively stable grasp once applied to an object. Like able-bodied individuals (Lavoie 2017), the TR users were able to transition their gaze to the drop-off targets at some point during Transport, and did not glance back at their terminal device once they had done so.

Although the prosthesis users did not appear to be glancing back and forth during Transport, two users displayed this behavior during some Reach phases (glancing at the pick-up target, then at their terminal device, and then back to the pick-up target), and most TR users demonstrated a behaviour of glancing first at their terminal device before the pick-up target in at least one Reach phase. This was not something these users did consistently in every trial, but was more common than in able-bodied individuals. The need to look at one's end effector while preparing to grasp an object is likely related to decreased proprioception. If it is true that body-powered prostheses provide more proprioceptive feedback than myoelectric devices, as has been suggested in the literature (Nghiem et al. 2015; Carey et al. 2015), then we expect to see this behaviour even more in users of myoelectric prostheses. The BP user for whom this back and forth behaviour was observed most often was P94, who was rated as the least skilled of the five TR BP users based on the AM-ULA. Since P94 was less skilled with their prosthesis, they might not have had as strong a sense of grip aperture from the cable.

Another similarity among the TR BP prosthesis users was that they moved their terminal devices less smoothly than able-bodied individuals, as evidenced by higher Numbers of Movement Units. During individual Reach-Grasp and Transport-Release movements, able-bodied individuals tend to move smoothly from start to finish of the movement, and demonstrate hand trajectories with one or sometimes two movement units when moving around a barrier (Valevicius et al. 2018). Conversely, the TR BP users consistently had higher Numbers of Movement Units within all segments, indicating that they switch between acceleration and deceleration multiple times in a given Reach-Grasp or Transport-Release movement, as has previously been observed in upper limb prosthesis users (Fraser & Wing 1981; Bouwsema et al. 2010; Cowley et al. 2016). This increase in sub-movements represents a less smoothly controlled trajectory of the terminal device, which was also evidenced by higher between-trial variability in end effector trajectories of the TR users. From examining the velocity profiles of the TR users' terminal devices, it appears that most of the additional movement units occur in Grasp and Release phases of the tasks, compared to the Reach and Transport phases. That the transradial prosthesis users were able to move their end effectors more smoothly during Reach and Transport is consistent with the fact that they can control the positioning of their terminal device during these phases entirely with their anatomic joints (as they have an intact elbow and shoulder), and it is during the grasp and release phases when controlling the prosthetic terminal device that their movement becomes less smooth.

5.2 Comparison to Transhumeral Body-Powered Prosthesis Users

Since there is a decrease in the acceptance of prosthetic devices with more proximal amputations (E. Biddiss & Chau 2007), we were interested in understanding how the visuomotor behaviour of the TR BP prosthesis users would compare with the behaviour of transhumeral (TH) body-powered prosthesis users. Only three TH BP prosthesis users were recruited for this study, but based on these three individuals, some preliminary observations can be made.

Relative to the normative data set, the TH BP users exhibited similar trends in task performance and visuomotor behaviour as the TR BP users: longer trial durations, increased fixations to hand, higher Number of Movement Units, similar or reduced Peak Hand Velocities, and similar or greater Hand Distances Travelled and Hand Trajectory Variability. With respect to the magnitude of these differences from normative behaviour, two of the three TH users often resembled the TR users. The only TH user who was consistently further from normative behaviour than the TR users was P03, who was only one year post-amputation at the time of testing and only used their prosthesis an average of two hours per day (Table 3.1). For the other two more experienced TH users, the measures which appeared to offer the most differentiation between them and the TR users were related to eye gaze behaviour. Compared with TR users, the TH users had more Transport phases in which fixation to their terminal device exceeded the normative range, and it was more common for this to impact their ability to look ahead to the drop-off target. The TH users also seemed to look at their terminal device more often while reaching for objects, especially for the Cup Transfer Task. This increase in visual attention to their terminal device may indicate a decreased confidence in its location in space due to a lack of proprioception at the elbow joint. Since two of the three TH users were able to complete the tasks as quickly and with similar end effector movement quality as some of the TR users, the fact that they appear to feel an increased demand on their visual attention from their prosthesis may provide insight into the reasons for increased rejection of more proximal prostheses. In addition, this serves to highlight the importance of assessing a variety of measures when attempting to evaluate the efficacy and functionality of prosthetic devices.

5.3 Visuomotor Behaviour is Task-Dependent

For both the TR and TH BP prosthesis users, it was observed that visuomotor behaviour was not always consistent between the Cup Transfer Task and Pasta Box Task. Although there were trends in behaviour which persisted between the tasks (longer trial durations, increased fixations to hand, number of movement units), some of these were more pronounced in one task compared with the other, and there were other behaviours which were primarily observed in only one of the tasks.

Both TR and TH users tended to fixate on their terminal devices for a greater percentage of transport in the Cup Transfer Task compared with the Pasta Box Task. This is likely due to the increased risk of transporting the bead-filled compliant cups compared to the pasta box, which could be bumped or dropped without the consequence of spilling. This appeared to have an impact on all of the prosthesis users, but it also appeared to disproportionately affect the behaviour of participant P66, who used visual feedback as a major compensation when moving the cups as compared to the pasta box, as was discussed in section 5.1.

Another difference between the tasks was in the relative duration of the Grasp phases. In the Cup Transfer Task, almost all of the prosthesis users spent a disproportionate amount of time in Grasp, while only two users consistently demonstrated this behaviour for the Pasta Box Task. This is believed to be related to the increased risk of not having a firm grasp on the bead-filled cups. At the same time, the prosthesis users generally continued to look at the pasta box for longer after releasing it on a target than they did with the cups. This could be because they were always moving to the 'Home' target following a Release phase in the Pasta Box Task, instead of immediately reaching for another object like in two of the movements in the Cup Transfer Task, but it might also be related to the pasta box being less intrinsically stable than the cups, and more likely to fall over after being set down.

The Pasta Box task also teases out able-bodied individuals' lesser reliance on visual feedback when grasping and releasing objects (and in contrast, prosthesis users' increased reliance) by having the target on the side table. Able-bodied individuals fixate less on this target than the other targets that are on the shelves in front of them, presumably because it is outside of their field of view and requires more effort to turn and fixate on (Lavoie et al. 2018). However, all of the prosthesis users fixated more than normative on this side table target during the final Release phase of the Pasta Box Task, and the majority of them also had higher Percent Fixations to 'Current' during the first Reach phase (to the side table).

The inclusion of the side table and shelves in the Pasta Box Task also created greater demands on range of motion. This presents a unique challenge for body-powered prosthesis users, because moving their terminal device between these areas can cause changes in cable length and may force them to operate outside of regions their cable length has been optimized for. This seemed to reduce the prosthesis users' ability to coordinate grip aperture opening with reaching as described in Chapter 4 section 4.1.2.4. The Pasta Box Task also appeared to challenge the TH prosthesis users more than the TR users, as the difference between TR and TH in terms of fixation to their terminal device during transport was more pronounced in the Pasta Box Task than the Cup Transfer Task. Additionally, the TH users' end effector velocity profiles appeared to be less smooth in the Pasta Box Task (although their Numbers of Movement units were similar to some of the TR users, they appeared to have more movement units during Reach and Transport, and the prominence of the movement units appeared to be larger).

It is important to appreciate that the parameters of a functional upper limb task have an effect on visuomotor behaviour and might pose unique challenges to different patient populations. (e.g. the demands of the Pasta Box Task allowed us to see greater functional differences between the TH and TR users than the Cup Transfer Task). These findings reinforce the need to include tasks that are more complex than simple reach-to-grasp and have a variety of demands when characterizing visuomotor behaviour, as well as the need for agreed-upon standardized functional upper limb tasks to make it possible to compare outcomes across studies.

5.4 Comparison of Eye Gaze Behaviour to Myoelectric Prosthesis Users in Literature

Another objective of this study was to compare the obtained results to findings on eye gaze behaviour of prosthesis users in the literature, which has solely focused on myoelectric prosthetic devices (see Chapter 2, section 2.3.2). It was for this purpose that Target Locking Strategy (TLS) was calculated for the Reach phases in the Cup Transfer Task, in order to compare with Parr et al. 2017 (Chapter 3, section 3.5.2). In general, higher TLS indicates greater fixation on upcoming targets of action and less focus on an individual's hand (or terminal device).

TLS values for the five TR BP prosthesis users who participated in this study were all well above the value of 40% presented by Parr et al. for their simulated myoelectric prosthesis users, and often within two standard deviations of our normative mean. The TH users had mean TLS values which were mostly similar to the TR users, except in Reach 4, where their mean TLS values were 49% and 47%. Still, these outcomes indicate that, in general, the body-powered prosthesis users in this study were able to fixate more on up-coming pick-up targets and/or less on their terminal devices during Reach than the simulated myoelectric prosthesis users in Parr's study. Unfortunately, a limitation of this metric is that we cannot say for certain whether Parr's participants were fixating more on their terminal device during reach or just fixating less on their pick-up target. However, since it has been shown that people tend to spend most of their time fixating on task-relevant areas of interest (Lavoie 2017), we assume that former is true. This conclusion is consistent with the prediction made in section 5.1: that myoelectric prosthesis users will fixate more on their terminal devices during Reach than body-powered users because of reduced proprioceptive feedback. However, the participants in Parr's study were actually able-bodied individuals with no previous experience with a prosthesis simulator, and although they were given a brief practice period, the TLS results from Parr's study might be artificially low due to the novelty of myoelectric control. Comparison to experienced myoelectric users would be preferable.

As was discussed in Chapter 2, there have been a small number of studies which have sought to characterize visuomotor behaviour of actual myoelectric prosthesis users. In a pilot study with two transradial myoelectric prosthesis users completing a cylinder manipulation task, Chadwell et al. (2016) observed that "During the "reach-to-grasp" component of the task, Prosthesis User 1 looked ahead of the hand for 76% of the time, while Prosthesis User 2 relied on looking at the hand for over 50% of the time." Since TLS is calculated as the difference between percentage of time an individual spends looking ahead, and percentage spent looking at their terminal device (Parr et al. 2017), it can be concluded that the potential range of TLS values for Prosthesis User 1 would be 52% to 76% (52% if they spent the other 24% of the reach-to-grasp looking at their terminal device, and 76% if they did not fixate on their terminal device at all during the other 24% of the movement). This would place Chadwell's Prosthesis User 1 on the lower end of TLS values observed for the BP users who participated in our study. On the other hand, Prosthesis User 2's maximum TLS would be less than 0% (as they spent over 50% of the reach looking at their hand and consequently would have looked at the pick-up target for less than 50%) which is well below both our outcomes and Parr's.

In another study, in which four experienced transradial myoelectric prosthesis users performed a carton pouring task (Sobuh, et al. 2014), results indicated that the myoelectric prosthesis users spent an average of 69% of the reach phase of the task fixating on the up-coming pick-up target, and an average of 12% fixating on their terminal device. This would correspond with a TLS during reach of 57%, which is lower than most of the TR BP user outcomes from our study. However, the standard deviations on the outcomes from Sobuh's study were roughly 20%, meaning that the uncertainty in their TLS value would be approximately 28%, and there may not be a significant difference between the myoelectric users in their study, and BP users in our study.

In conclusion, there is evidence in the literature that transradial myoelectric prosthesis users pay a disproportionate amount of attention to their terminal device while reaching for objects compared to normative behaviour, which was not seen as drastically with the transradial body-powered prosthesis users who participated in this study. This would support the notion that one reason for the continued acceptance of body-powered prostheses is that they provide more proprioceptive feedback than myoelectric prostheses, which allows users to prepare to grasp objects without visual feedback of their terminal device. However, the sample sizes in these studies have been very small, and the variability between participants has been large. Therefore, it is not possible to draw firm conclusions based on the available data.

5.5 Limitations

The main limitation of this study was its small sample size of 5 transradial and 3 transhumeral body-powered prosthesis users. Although this data was useful in the preliminary identification of potential trends in visuomotor behaviour of body-powered prosthesis users, the small number of participants precluded us from performing meaningful statistical analyses or drawing firm conclusions. Small sample size is a common limitation in studies with participants who are prosthesis users, as it can be challenging to recruit large numbers of individuals with amputations who are willing and able to donate their time to participate in research studies. The eight participants in this study were recruited and scheduled to participate in the study over a period of eight months. Our research group is continuing to recruit prosthesis users to improve the strength of conclusions that can be drawn.

Another limitation in this study was the accuracy of the gaze vectors. It is important to recognize that, as is the case with any eye tracking analysis, the gaze vectors which were used to calculate all eye gaze related metrics were really only predictions of where the participants were looking. The accuracy of these predictions was dependent on the quality of the pupil tracking data and the gaze calibration used to generate the predictions, and the quality of the data and calibrations was dependent on a number of factors, including the participants' face shape and ability to track a moving marker with their gaze for about a minute. Because of this, there was an unknown amount of error inherent in the gaze vector for each participant. Measures were taken to help account for this uncertainty, such as filling short gaps in fixations, deleting short fixations, and expanding the bounding boxes around areas of interest to account for small offsets in the gaze vector. However, one data set (P03's Cup Transfer Task trials) did have to be removed from the eye gaze analysis due to a poor gaze calibration, which resulted in gaze vectors that were consistently offset from all task relevant areas of interest. One advantage of the custom software tool (GaMA) which was used in this analysis was that it allowed us to easily visualize the gaze vectors and subjectively confirm the quality of the participants' eye tracking data. However, the current protocol did not provide a means to objectively quantify the accuracy of the gaze vectors. This is an area of continuing work in our GaMA software development.

Chapter 6. Conclusion

Eye-tracking and motion capture technologies have great promise in assessing the visuomotor behaviour of individuals with upper limb prosthetic devices, and by extension, the efficacy of innovative prostheses. However, limited work has been done to assess prevailing technologies using these methods. In particular, transradial body-powered prosthetic devices are generally considered to offer a high level of functionality to their users, and yet, visuomotor behaviour of these individuals has not been characterized in the literature to date.

The objective of this study was to characterize the eye gaze behaviour and end effector movement of five transradial (TR) body-powered (BP) prosthesis users during two functional upper limb tasks (a Cup Transfer Task and Pasta Box Task), using a combination of motion capture and eye-tracking technologies. A custom software tool was employed to analyze the data from these systems in combination, which allowed for automatic and precise quantification of many descriptors of eye gaze and movement behaviour. Results were compared with a set of previously established normative data as well as characterizations of TR myoelectric user eye gaze behaviour from the literature. The experimental protocol and analysis were repeated for three transhumeral (TH) BP prosthesis users, for preliminary comparison.

Compared to able-bodied individuals, there were some general trends that characterized the behaviour of the TR BP prosthesis users in this study. The TR prosthesis users took up to three times as long as able-bodied individuals to perform the functional tasks. However, they did not proportionally prolong all task phases, but instead tended to spend disproportionate amounts of time in the reach, grasp or release phases of the tasks. The eye gaze behaviour of the TR prosthesis users demonstrated that they dedicated more visual attention to their terminal device throughout the tasks, especially after picking up an object. However, they were still mostly able to look ahead to up-coming pick-up and drop-off targets for similar percentages of the task as able-bodied individuals, and they did not tend to glance back to their terminal device in Transport once they had looked ahead. With respect to end effector movement quality, the TR users showed increased variability in their end effector trajectories, and higher numbers of movement units than able-bodied individuals.

Although the TR BP prosthesis users demonstrated consistent trends in behaviour relative to normative data, there was variability among the participants which was mostly explained by skill level. The users that had been rated as more skilled on the AM-ULA tended to be faster, fixate on their terminal device less, and have smoother end effector movement. There was an exception in the Cup Transfer Task where one of the more skilled TR users dedicated a relatively high amount of visual attention to their prostheses while performing the task, while still demonstrating a high level of skill based on other metrics (time and end effector). This discrepancy in outcomes indicated a different visual motor strategy for that user to accomplish that task.

The three TH BP users demonstrated similar trends in behaviour as the TR users, and two out of the three mostly resembled the TR users in terms of the magnitude of their outcome metrics. There was some indication that the TH users might dedicate more visual attention to their terminal devices than the TR users. However, additional data is needed to investigate this trend.

The results of this study have raised a number of questions for future research: what could be done to reduce the visual demand requirements of body-powered prostheses, especially for TH prosthesis users? If visual demand was reduced, would it correlate with a decrease in rejection rates of prosthetic devices? Do myoelectric prosthesis users fixate more on their terminal devices while reaching and transporting objects compared to body powered users? If so, would integrating sensory feedback into these devices alleviate this demand on visual attention and allow them to behave more like body-powered users or even able-bodied individuals?

Answering these questions will require additional participants from each of the populations of interest, and should be able to be addressed with our assessment protocol. We are continuing to recruit individuals with upper limb amputations to further investigate these research questions. We are also working to validate our protocol with other versions of the required technologies (i.e., different eye tracking devices and motion capture systems) so that we can engage with other research sites to perform multi-site studies, to increase sample sizes. In addition, correlating the visuomotor behaviour with angular kinematics and assessment of body compensation would shed further light on the strategies used to accomplish these tasks.

With respect to uncertainty in the prediction of the gaze vectors used in this analysis (Chapter 5, section 5.5), a number of efforts aimed at addressing this are underway. This includes a study examining different gaze calibration protocols and identifying the most reliable one, and the development of a system for verifying the accuracy of a newly collected gaze calibration before collection of task trial data.

Finally, it is worth discussing the fact that the approach used in this study produces a considerable amount of data which can be time-consuming to interpret. Although this wealth of outcome metrics is useful in establishing a detailed picture of visuomotor behaviour, it might also be useful to distill this information into a limited number of summarizing outcomes or scores. A more limited set of outcomes would likely be appreciated in a clinical setting, where professionals might want to evaluate the effectiveness of a new technology or training regimen without having to engage in extensive data interpretation. To this end, a data science approach is being applied by members of our research team, to identify particularly informative combinations of certain metrics. Of course, combining metrics must be done with thought about how to condense data without obfuscating or reducing information, in order to avoid uncertainties that arise with combined metrics such as Parr's Target Locking Strategy (Parr et al. 2017) (see section 5.4).

In closing, this study is the first to assess and characterize the visuomotor behaviour of body-powered prosthesis users performing functional upper limb tasks. This data set will be useful in comparison with other prosthesis user populations and as new innovations in prosthetic device technology emerge. By using a combination of motion capture and eye tracking technologies, we were able to precisely quantify many aspects of visuomotor behaviour, that we believe to be important in daily device function and long term acceptance of prostheses. This analysis and future efforts will help to answer important questions about the efficacy of various upper limb prosthetic device technologies, and in turn, help to improve the state of technology available to individuals with upper limb loss.

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Appendix A. Pupil Data Cleaning Algorithm

The process followed by the pupil data cleaning script is described below. Specific parameters used for the current analysis are provided in Table A.1. Figure A.1 provides a visualization of a set of pupil data from a gaze calibration trial before and after the cleaning algorithm.

1) Calculate confidence in each data point using the algorithm defined in section A.1 (confidence will be a number ranging from 0 to 1)
2) Take only the data points with a confidence greater than or equal to the Combined Confidence Upper Bound (Table A.1)
3) For the data set from Step 2, interpolate to fill in gaps which are shorter than 50 ms, then delete any isolated sections of data which are shorter than 50 ms
4) For each data point which had a confidence between the Combined Confidence Lower and Upper Bounds (Table A.1), and that was not interpolated in step 3
    a. Check that it's radial distance from the mean of the pupil position does not exceed the Radial Distance Hard Cut-off (Table A.1)
    b. Check that adding the data point back in with the data would not violate the Velocity Hard Cut-off (Table A.1)
    c. If conditions both (i) and (ii) are met: add data point back in to the data set
5) For the data set from Step 4, interpolate to fill in gaps which are shorter than 50 ms, then delete any isolated sections of data which are shorter than 50 ms
6) Filter both the X and Y coordinates of the pupil data using a 4th order, zero-lag Butterworth filter with a cutoff frequency of 10 Hz

Table A.1: Parameters used by eye-tracker pupil data cleaning algorithm for current analysis

Parameter	Value/Equation Used in Current Analysis
Radial Distance Upper Bound	0.225
Radial Distance Lower Bound	0.150
Radial Distance Hard Cut-off	$\overline{d_{rad}} + 4 * \sigma_{d_{rad}}$ [1]
Velocity Upper Bound	6
Velocity Lower Bound	1.5
Velocity Hard Cut-off	6
Missing Data Window	100 ms
Missing Data Upper Bound	100%
Missing Data Lower Bound	51%
Combined Confidence Upper Bound	0.9
Combined Confidence Lower Bound	0.6

[1] $\overline{d_{rad}}$ = average radial distance of data points from mean pupil position
$\sigma_{d_{rad}}$ = standard deviation of radial distance from mean pupil position

A.1 Algorithm for Calculating Data Confidence

1) For each data point, calculate:
    a. Radial distance from the mean pupil position for the data set, $(\bar{x}, \bar{y})$:

$$d_i = \sqrt{(x_i - \bar{x})^2 + (y_i - \bar{y})^2}$$

    b. Instantaneous velocity

$$v_i = \frac{\sqrt{(x_i - x_{i-1})^2 + (y_i - y_{i-1})^2}}{\Delta t}$$

where $\Delta t = 1/samplingFrequency$ which was 60 Hz for the Dikablis Professional 2.0 eye-tracker used in this study

    c. Percentage of non-missing data within a specific window surrounding the data point, p_i
        → For example: in a window of 100 ms surrounding a given data point, 75% of data points were non-NaN

    (Missing Data Window defined in Table A.1)

2) For each data point, check radial distance:
    → If $d_i <$ Radial Distance Lower Bound (Table A.1): $C_d = 1$
    → If $d_i \geq$ Radial Distance Upper Bound (Table A.1): $C_d = 0$
    → Otherwise: $C_d = 1 - \frac{d_i - \text{Radial Distance Lower Bound}}{\text{Radial Distance Upper Bound} - \text{Radial Distance Lower Bound}}$

    (Scaled value between 0 and 1, depending on where d_i falls relative to lower and upper bounds)

2) For each data point, check instantaneous velocity:
    → If $v_i <$ Velocity Lower Bound (Table A.1): $C_v = 1$
    → If $v_i \geq$ Velocity Upper Bound (Table A.1): $C_v = 0$
    → Otherwise: $C_v = 1 - \frac{v_i - \text{Velocity Lower Bound}}{\text{Velocity Upper Bound} - \text{Velocity Lower Bound}}$

    (Scaled value between 0 and 1, depending on where v_i falls relative to lower and upper bounds)

3) For each data point, check percentage of non-missing data in surrounding window:
    → If $p_i \geq$ Missing Data Upper Bound (Table A.1): $C_p = 1$
    → If $p_i <$ Missing Data Lower Bound (Table A.1): $C_p = 0$
    → Otherwise: $C_p = \frac{p_i - \text{Missing Data Lower Bound}}{\text{Missing Data Upper Bound} - \text{Missing Data Lower Bound}}$

    (Scaled value between 0 and 1, depending on where p_i falls relative to lower and upper bounds)

4) Take the mean of C_d, C_v, and C_p to obtain overall confidence for each data point

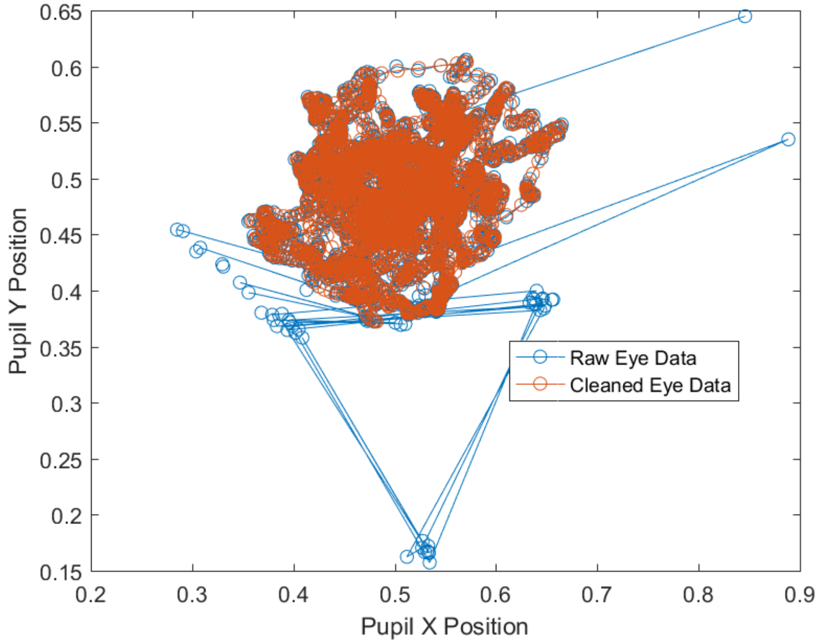


Figure A.1: Pupil data from a gaze calibration trial shown before and after application of the pupil data cleaning algorithm.

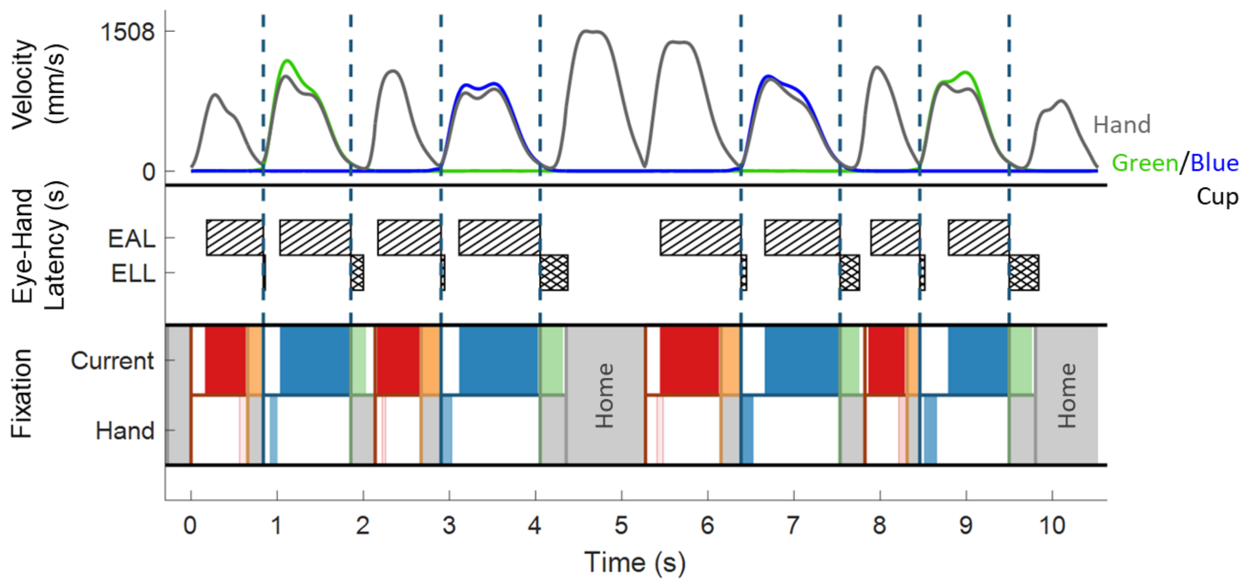
Appendix B. Detailed Report for Participant P66

Table B.1: Participant Information

Age (years)	59
Gender	Male
Level of amputation	Transradial
Amputation side	Right
Length of residual limb (cm)	16
Years since amputation at date of testing	28
Type of prosthesis	Body powered
Type of end-effector	Split hook, voluntary open
Hours per day of use	12
AM-ULA	26.1
UEFS	67.8

B.1 Cup Transfer Task Outcomes

Normative Data Set:



P66:

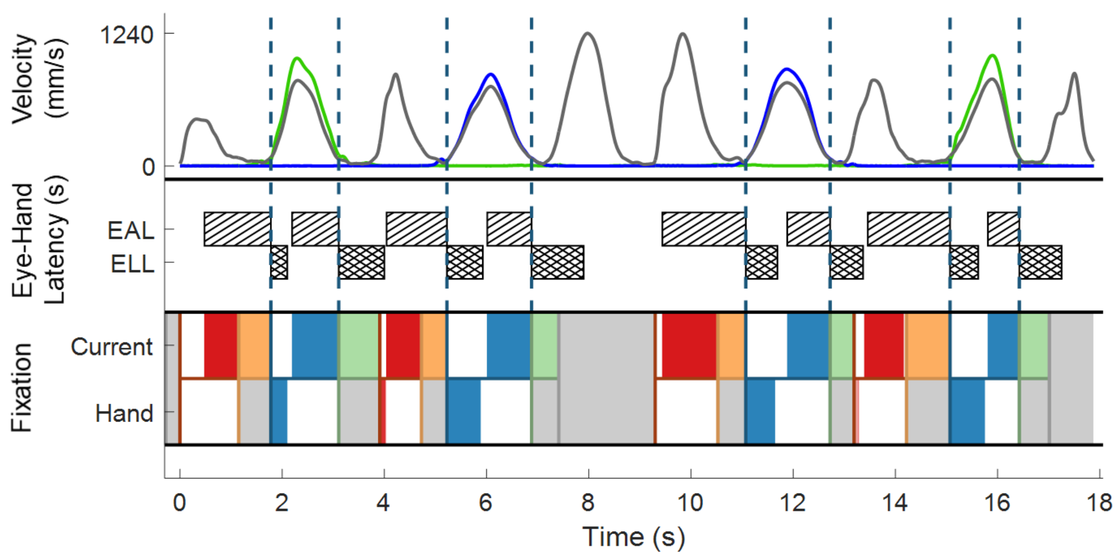


Figure B.1: Summary figures for prosthesis user participant compared with normative data. Top row: velocity plots for hand (grey) and objects (green cup and blue cup). Middle row: Eye Arrival Latencies and Eye Leaving Latencies (at Pick-Up and Drop-Off). Bottom row: fixation plots representing Percent Fixations to 'Current' and 'Hand Only' AOIs throughout each task phase: Reach (red), Grasp (orange), Transport (blue), and Release (green). Opacity level of fixation plots represents probability of fixation. The entire task is plotted with time along the x-axis.

Table B.2: Task performance

Number of successful trials	9
Trial success rate (%)	90%
Errors	1 – Movement hesitation
Number of trials analyzed	9

Table B.3: Phase Durations and Relative Phase Durations*

		Duration (s)				Relative Phase Duration (%)			
		Norm	SD	P66	SD	Norm	SD	P66	SD
M 1	R	0.66	0.09	1.15	0.12	30.79	1.72	29.47	3.18
	G	0.18	0.05	0.63	0.09	8.38	1.83	16.16	2.59
	T	1.02	0.10	1.33	0.13	47.77	2.42	33.97	2.52
	RL	0.28	0.07	0.80	0.16	13.06	2.34	20.40	3.08
M 2	R	0.53	0.09	0.82	0.06	24.00	1.67	23.35	1.07
	G	0.23	0.07	0.50	0.05	10.26	1.92	14.23	0.89
	T	1.15	0.12	1.66	0.21	52.15	2.72	47.25	3.34
	RL	0.30	0.07	0.53	0.13	13.59	2.88	15.16	3.19
M 3	R	0.88	0.12	1.23	0.07	34.43	2.03	31.60	2.26
	G	0.23	0.06	0.55	0.12	9.06	1.57	13.97	2.39
	T	1.15	0.12	1.65	0.10	45.30	2.42	42.46	2.71
	RL	0.29	0.09	0.47	0.10	11.21	3.00	11.97	1.75
M 4	R	0.49	0.06	1.03	0.14	24.91	2.60	26.96	3.13
	G	0.15	0.05	0.85	0.39	7.29	1.71	21.68	7.31
	T	1.04	0.12	1.36	0.20	52.57	2.65	35.83	6.34
	RL	0.31	0.09	0.59	0.12	15.23	3.74	15.52	3.39
Total		10.53	1.32	17.88	0.97				

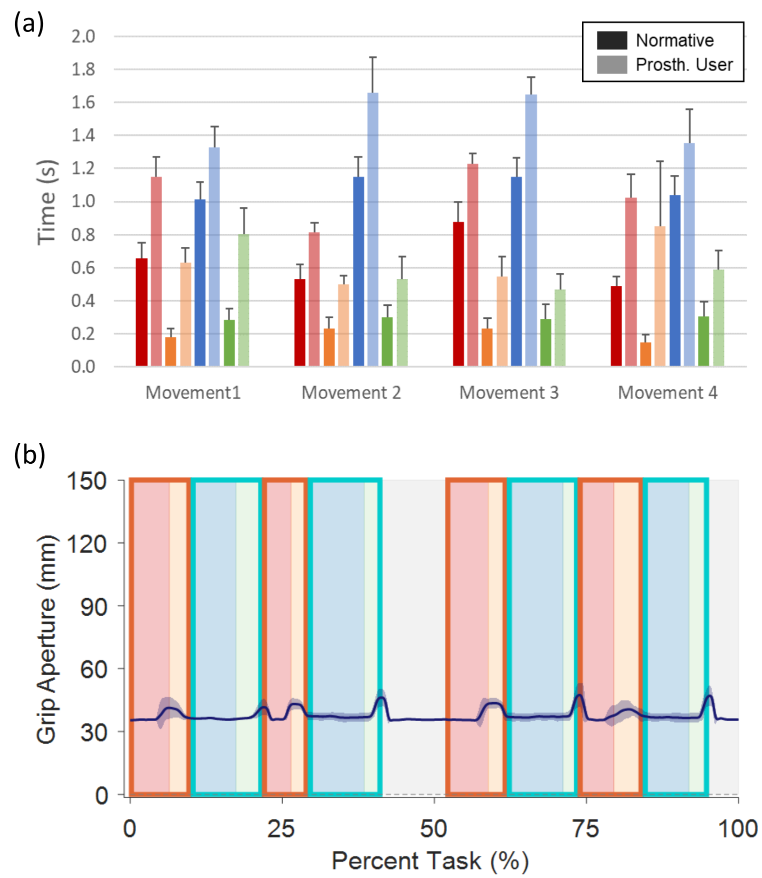


Figure B.2: (a) Phase Durations compared with normative data, (b) Grip Aperture profile. Phases are color coded: Reach (red), Grasp (orange), Transport(blue), and Release (green).

* For all tables: standard deviations are presented as between-participant SD for normative data and between-trial SD for prosthesis user participant data unless otherwise stated. Red highlighted cells indicate prosthesis user outcomes which were more than two SD from the normative mean.
M = Movement, R = Reach, G = Grasp, T = Transport, RL = Release.

Table B.4: Eye Gaze Fixation and Eye-Hand Latency Metrics*

		Mean Percent Fixations (When Fixated) (%)								Mean Number of Fixations							
		Current AOI				Hand Only AOI				Current AOI				Hand Only AOI			
		Norm	SD	P66	SD	Norm	SD	P66	SD	Norm	SD	P66	SD	Norm	SD	P66	SD
M 1	R	71.8	14.6	58.3	3.4	14.3	6.7	0.0	0.0	1.00	0.11	1.00	0.00	0.02	0.04	0.00	0.00
	G	82.5	21.3	100.0	0.0					0.89	0.16	1.00	0.00				
	T	78.8	11.4	68.6	7.9	8.2	4.8	24.1	8.5	1.02	0.03	1.00	0.00	0.52	0.32	1.00	0.00
	RL	58.0	18.2	100.0	0.0					0.87	0.18	1.00	0.00				
M 2	R	92.6	7.4	83.8	8.8	7.5	4.2	14.7	8.2	1.01	0.02	1.00	0.00	0.08	0.09	0.89	0.33
	G	86.7	13.9	100.0	0.0					0.95	0.10	1.00	0.00				
	T	79.5	11.9	52.9	8.3	10.3	4.0	39.1	9.2	1.01	0.02	1.00	0.00	0.58	0.29	1.00	0.00
	RL	82.2	16.7	100.0	0.0					0.94	0.22	1.00	0.00				
M 3	R	77.6	15.3	87.3	15.5	7.3	4.8	0.0	0.0	1.00	0.07	1.11	0.33	0.07	0.17	0.00	0.00
	G	90.4	14.5	100.0	0.0					0.90	0.24	1.00	0.00				
	T	74.5	10.7	50.8	5.4	11.8	6.1	34.4	7.6	1.03	0.05	1.00	0.00	0.74	0.33	1.33	0.50
	RL	75.7	15.3	100.0	0.0					0.94	0.15	1.00	0.00				
M 4	R	85.3	12.1	76.2	11.3	16.8	12.2	8.6	1.9	0.96	0.09	1.11	0.33	0.11	0.18	0.33	0.50
	G	78.1	21.9	98.5	4.6					0.83	0.27	1.00	0.00				
	T	66.2	14.6	45.8	13.4	13.7	9.6	50.4	16.6	0.96	0.14	1.00	0.00	0.68	0.43	1.00	0.50
	RL	82.5	18.9	100.0	0.0					0.94	0.17	1.00	0.00				

		EAL_{Grasp} (s)				EAL (s)				ELL (s)				$ELL_{Release}$ (s)			
		Norm	SD	P66	SD	Norm	SD	P66	SD	Norm	SD	P66	SD	Norm	SD	P66	SD
M 1	P	0.475	0.138	0.669	0.074	0.656	0.155	1.299	0.079	-0.020	0.103	-0.321	0.113				
	D					0.822	0.151	0.911	0.143	-0.146	0.101	-0.893	0.162	0.136	0.089	-0.090	0.082
M 2	P	0.500	0.104	0.682	0.074	0.732	0.165	1.181	0.114	-0.040	0.097	-0.704	0.206				
	D					0.941	0.119	0.867	0.111	-0.320	0.258	-1.019	0.209	-0.018	0.251	-0.487	0.139
M 3	P	0.700	0.153	1.086	0.185	0.934	0.185	1.632	0.245	-0.062	0.181	-0.618	0.207				
	D					0.870	0.160	0.839	0.108	-0.224	0.114	-0.645	0.119	0.065	0.110	-0.177	0.059
M 4	P	0.418	0.091	0.756	0.137	0.566	0.102	1.609	0.324	-0.057	0.193	-0.551	0.437				
	D					0.703	0.173	0.615	0.189	-0.341	0.190	-0.828	0.183	-0.036	0.174	-0.240	0.099

* For all tables: standard deviations are presented as between-participant SD for normative data and between-trial SD for prosthesis user participant data unless otherwise stated. Red highlighted cells indicate prosthesis user outcomes which were more than two SD from the normative mean.

M = Movement, R = Reach, G = Grasp, T = Transport, RL = Release, P = Pick-up, D = Drop-off.

Table B.5: End Effector Metrics*

		Hand Distance Travelled (mm)				
		Norm	$SD_{b/n}$	$SD_{w/in}$	P66	SD
M 1	R-G	366	52	23	332	25
	T-RL	646	39	21	641	29
M 2	R-G	456	56	30	456	28
	T-RL	700	46	27	704	21
M 3	R-G	887	35	25	896	22
	T-RL	724	46	28	761	17
M 4	R-G	428	49	24	513	18
	T-RL	657	46	25	643	36

		Hand Trajectory Variability (mm)			
		Norm	$SD_{b/n}$	P66	SD
M 1	R-G	16	3	18	
	T-RL	17	4	22	
M 2	R-G	17	4	14	
	T-RL	20	5	45	
M 3	R-G	26	5	28	
	T-RL	20	4	24	
M 4	R-G	14	4	31	
	T-RL	20	4	31	

		Number of Movement Units				
		Norm	$SD_{b/n}$	$SD_{w/in}$	P66	SD
M 1	R-G	1	0	0	5	1
	T-RL	2	0	1	5	2
M 2	R-G	1	0	0	2	1
	T-RL	2	0	1	3	1
M 3	R-G	2	0	0	3	1
	T-RL	2	1	1	3	1
M 4	R-G	1	0	0	5	3
	T-RL	2	0	1	4	1

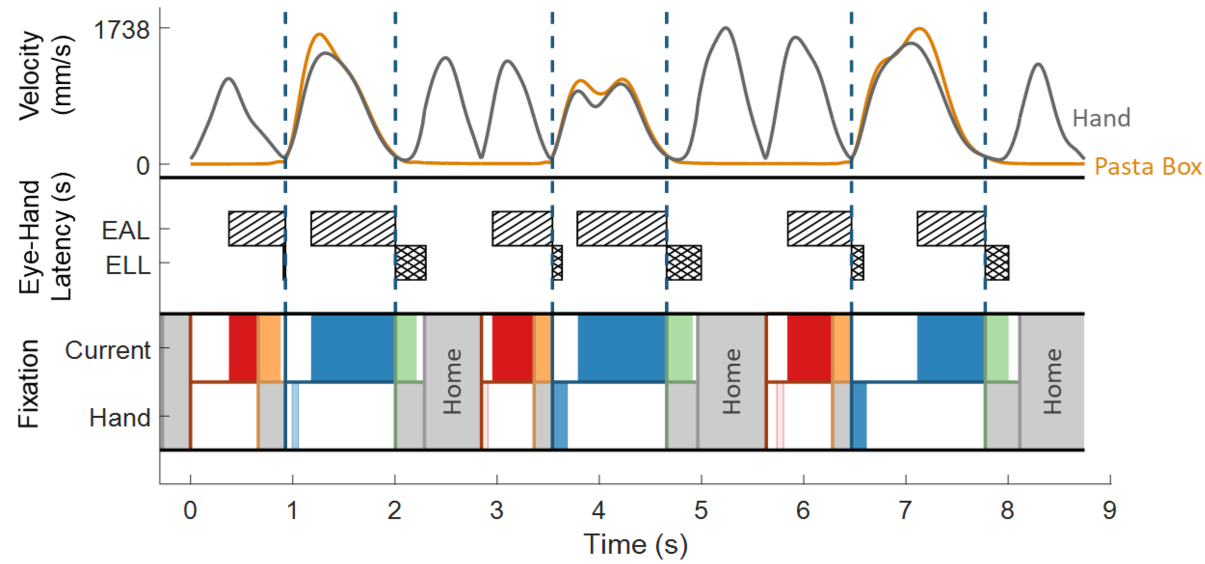
		Peak Hand Velocity (mm/s)					Percent to Peak Hand Velocity (%)				
		Norm	$SD_{b/n}$	$SD_{w/in}$	P66	SD	Norm	$SD_{b/n}$	$SD_{w/in}$	P66	SD
M 1	R-G	866	166	71	481	43	35.2	4.4	4.8	20.4	6.6
	T-RL	1042	88	52	813	59	21.0	2.6	3.0	25.0	2.9
M 2	R-G	1149	139	75	884	72	30.3	7.2	5.9	25.0	2.7
	T-RL	940	70	49	786	51	37.7	9.1	7.0	42.5	5.8
M 3	R-G	1492	187	82	1253	83	36.3	8.4	6.9	30.9	2.0
	T-RL	1009	56	52	797	66	24.7	2.4	2.8	37.2	4.2
M 4	R-G	1157	147	72	909	93	24.5	4.7	5.4	20.5	5.4
	T-RL	979	76	49	853	69	28.0	7.6	8.4	42.5	6.2

		Percent to Peak Hand Deceleration (%)					Percent to Peak Grip Aperture (%)					Peak Grip Aperture (mm)				
		Norm	$SD_{b/n}$	$SD_{w/in}$	P66	SD	Norm	$SD_{b/n}$	$SD_{w/in}$	P66	SD	Norm	$SD_{b/n}$	$SD_{w/in}$	P66	SD
M 1	R-G	62.0	8.7	13.7	40.9	6.2	80.4	4.7	5.1	60.7	5.5	99	4	3	41	3
M 2	R-G	49.8	6.5	6.9	32.1	5.1	73.0	6.3	9.1	70.4	5.8	114	6	4	43	1
M 3	R-G	61.0	5.3	5.9	46.9	5.0	80.4	3.9	4.9	79.3	10.2	114	7	2	44	1
M 4	R-G	62.3	13.5	11.8	31.7	5.2	83.7	5.4	9.2	76.3	13.7	100	5	4	41	2

* For all tables: standard deviations are presented as between-participant SD for normative data and between-trial SD for prosthesis user participant data unless otherwise stated. Red highlighted cells indicate prosthesis user outcomes which were more than two SD from the normative mean.
M = Movement, R = Reach, G = Grasp, T = Transport, RL = Release.

B.2 Pasta Box Task Outcomes

Normative Data Set:



P66:

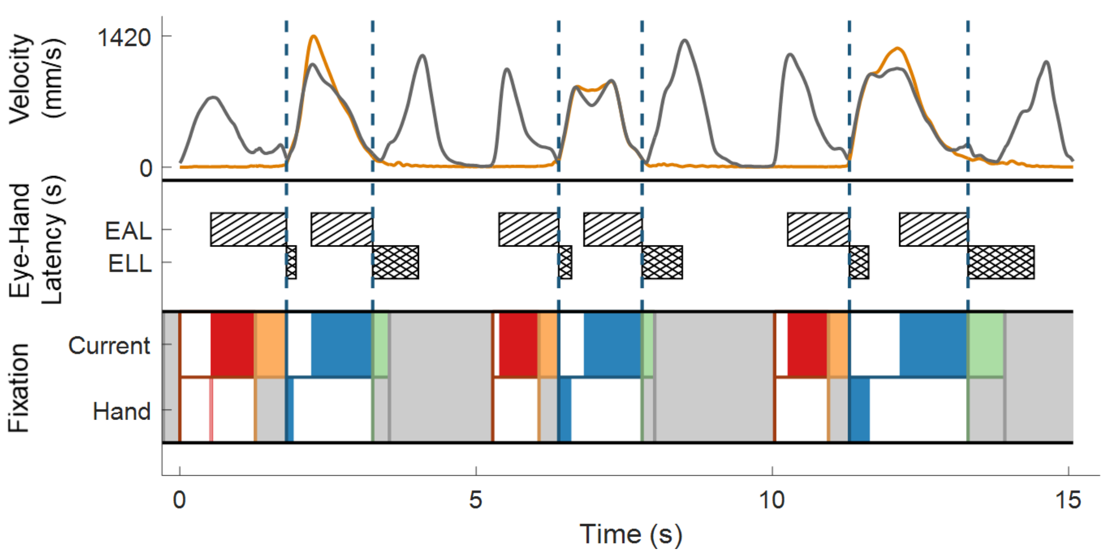


Figure B.3: Summary figures for prosthesis user participant compared with normative data. Top row: velocity plots for hand (grey) and objects (green cup and blue cup). Middle row: Eye Arrival Latencies and Eye Leaving Latencies (at Pick-Up and Drop-Off). Bottom row: fixation plots representing Percent Fixations to 'Current' and 'Hand Only' AOIs throughout each task phase: Reach (red), Grasp (orange), Transport (blue), and Release (green). Opacity level of fixation plots represents probability of fixation. The entire task is plotted with time along the x-axis.

Table B.6: Task performance

Number of successful trials	9
Trial success rate (%)	82%
Errors	1 – Hit frame of shelves
	1 – Undesired movement
Number of trials analyzed	9

Table B.7: Phase Durations and Relative Phase Durations*

		Duration (s)				Relative Phase Duration (%)			
		Norm	SD	P66	SD	Norm	SD	P66	SD
M 1	R	0.66	0.08	1.28	0.10	29.03	2.01	37.21	5.48
	G	0.27	0.08	0.52	0.69	11.47	2.47	12.58	11.10
	T	1.08	0.12	1.46	0.20	47.13	2.22	42.04	4.39
	RL	0.28	0.07	0.28	0.20	12.37	2.34	8.17	4.81
M 2	R	0.52	0.06	0.78	0.07	24.44	2.01	28.61	1.99
	G	0.18	0.05	0.33	0.06	8.32	1.67	12.18	1.61
	T	1.12	0.13	1.41	0.16	53.00	2.89	51.43	3.00
	RL	0.30	0.08	0.21	0.05	14.24	2.73	7.78	1.72
M 3	R	0.65	0.10	0.91	0.10	26.18	1.82	24.09	4.47
	G	0.19	0.06	0.35	0.13	7.36	1.78	9.43	3.48
	T	1.31	0.16	2.00	0.79	52.91	2.07	50.95	10.47
	RL	0.34	0.07	0.62	0.41	13.56	2.16	15.53	9.34
Total		8.75	1.20	15.08	2.01				

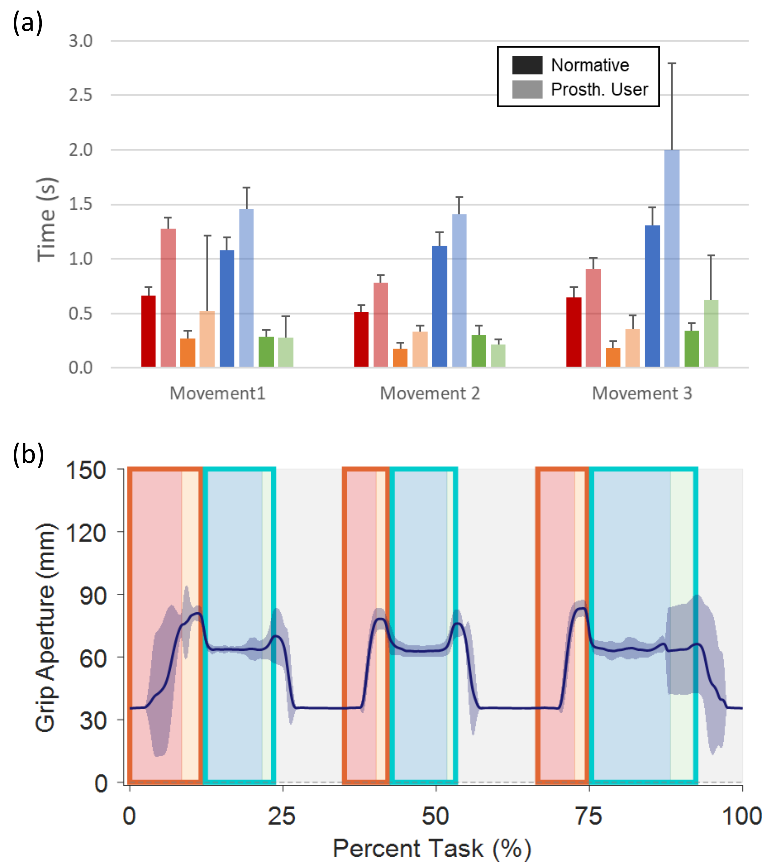


Figure B.4: (a) Phase Durations compared with normative data, (b) Grip Aperture profile. Phases are color coded: Reach (red), Grasp (orange), Transport(blue), and Release (green).

* For all tables: standard deviations are presented as between-participant SD for normative data and between-trial SD for prosthesis user participant data unless otherwise stated. Red highlighted cells indicate prosthesis user outcomes which were more than two SD from the normative mean.

Table B.8: Eye Gaze Fixation and Eye-Hand Latency Metrics*

		Mean Percent Fixations (When Fixated) (%)								Mean Number of Fixations							
		Current AOI				Hand Only AOI				Current AOI				Hand Only AOI			
		Norm	SD	P66	SD	Norm	SD	P66	SD	Norm	SD	P66	SD	Norm	SD	P66	SD
M 1	R	42.8	8.6	58.8	3.7	0.0	0.0	4.1	0.7	1.01	0.14	1.00	0.00	0.00	0.00	0.44	0.53
	G	82.7	15.0	100.0	0.0					0.97	0.07	1.00	0.00				
	T	75.1	9.7	71.1	8.4	5.8	2.4	7.6	5.7	1.03	0.05	1.00	0.00	0.32	0.33	1.00	0.00
	RL	71.8	18.0	100.0	0.0					0.99	0.03	1.00	0.00				
M 2	R	77.5	15.0	85.9	14.5	10.5	9.0	0.0	0.0	1.00	0.02	1.00	0.00	0.03	0.10	0.00	0.00
	G	89.4	15.3	100.0	0.0					0.93	0.15	1.00	0.00				
	T	76.9	9.3	69.7	6.9	12.7	6.7	14.9	9.8	1.02	0.06	1.00	0.00	0.75	0.28	1.00	0.00
	RL	81.8	15.1	100.0	0.0					0.99	0.03	1.00	0.00				
M 3	R	66.4	15.8	76.0	14.8	10.5	7.7	0.0	0.0	1.02	0.04	1.00	0.00	0.07	0.19	0.00	0.00
	G	93.6	14.0	100.0	0.0					0.98	0.05	1.00	0.00				
	T	50.0	4.7	54.2	10.9	11.2	3.6	18.8	20.4	1.06	0.09	1.00	0.00	0.85	0.27	1.00	0.50
	RL	64.2	15.8	100.0	0.0					1.00	0.09	1.00	0.00				

		EAL_{Grasp} (s)				EAL (s)				ELL (s)				$ELL_{Release}$ (s)			
		Norm	SD	P66	SD	Norm	SD	P66	SD	Norm	SD	P66	SD	Norm	SD	P66	SD
M 1	P	0.286	0.068	0.749	0.071	0.552	0.114	1.274	0.726	0.019	0.078	-0.161	0.109				
	D					0.823	0.200	1.034	0.183	-0.297	0.201	-0.769	0.161	-0.013	0.188	-0.488	0.080
M 2	P	0.405	0.106	0.670	0.132	0.584	0.141	1.004	0.165	-0.094	0.129	-0.216	0.159				
	D					0.873	0.171	0.979	0.124	-0.338	0.188	-0.678	0.165	-0.034	0.168	-0.466	0.175
M 3	P	0.437	0.134	0.687	0.132	0.623	0.174	1.040	0.125	-0.116	0.091	-0.323	0.401				
	D					0.662	0.100	1.152	0.782	-0.229	0.095	-1.114	0.466	0.109	0.065	-0.493	0.391

* For all tables: standard deviations are presented as between-participant SD for normative data and between-trial SD for prosthesis user participant data unless otherwise stated. Red highlighted cells indicate prosthesis user outcomes which were more than two SD from the normative mean.
M = Movement, R = Reach, G = Grasp, T = Transport, RL = Release, P = Pick-up, D = Drop-off.

Table B.9: End Effector Metrics*

		Hand Distance Travelled (mm)					Hand Trajectory Variability (mm)				Number of Movement Units				
		Norm	$SD_{b/n}$	$SD_{w/in}$	P66	SD	Norm	$SD_{b/n}$	P66	SD	Norm	$SD_{b/n}$	$SD_{w/in}$	P66	SD
M 1	R-G	492	26	23	642	144	19	5	51		1	0	0	4	3
	T-RL	935	27	16	943	25	22	4	49		1	0	0	2	1
M 2	R-G	505	23	19	498	9	15	5	10		1	0	0	2	1
	T-RL	802	61	24	861	22	20	4	23		2	0	0	3	1
M 3	R-G	746	24	14	742	14	19	4	15		1	0	0	2	0
	T-RL	1186	31	18	1322	219	35	8	133		2	0	1	6	3

		Peak Hand Velocity (mm/s)					Percent to Peak Hand Velocity (%)				
		Norm	$SD_{b/n}$	$SD_{w/in}$	P66	SD	Norm	$SD_{b/n}$	$SD_{w/in}$	P66	SD
M 1	R-G	1164	163	90	827	96	41.2	4.5	3.0	30.5	5.7
	T-RL	1447	136	81	1142	129	29.3	3.1	3.0	25.8	2.7
M 2	R-G	1352	191	64	1076	107	36.8	4.4	3.5	21.5	2.2
	T-RL	1069	112	55	963	55	44.8	8.6	10.5	42.4	19.2
M 3	R-G	1666	261	92	1232	144	35.5	4.0	3.6	20.7	2.5
	T-RL	1598	180	106	1301	157	36.2	3.8	3.8	30.6	7.7

		Percent to Peak Hand Deceleration (%)					Percent to Peak Grip Aperture (%)					Peak Grip Aperture (mm)				
		Norm	$SD_{b/n}$	$SD_{w/in}$	P66	SD	Norm	$SD_{b/n}$	$SD_{w/in}$	P66	SD	Norm	$SD_{b/n}$	$SD_{w/in}$	P66	SD
M 1	R-G	55.7	8.0	7.8	86.0	21.8	73.3	6.5	6.9	89.2	8.4	116	8	8	81	2
M 2	R-G	72.6	8.6	5.6	35.8	7.6	80.1	8.0	4.6	81.1	7.2	106	10	5	78	3
M 3	R-G	72.8	8.4	5.9	46.9	8.2	81.5	4.9	5.0	89.8	1.1	109	8	5	83	2

* For all tables: standard deviations are presented as between-participant SD for normative data and between-trial SD for prosthesis user participant data unless otherwise stated. Red highlighted cells indicate prosthesis user outcomes which were more than two SD from the normative mean.
M = Movement, R = Reach, G = Grasp, T = Transport, RL = Release.

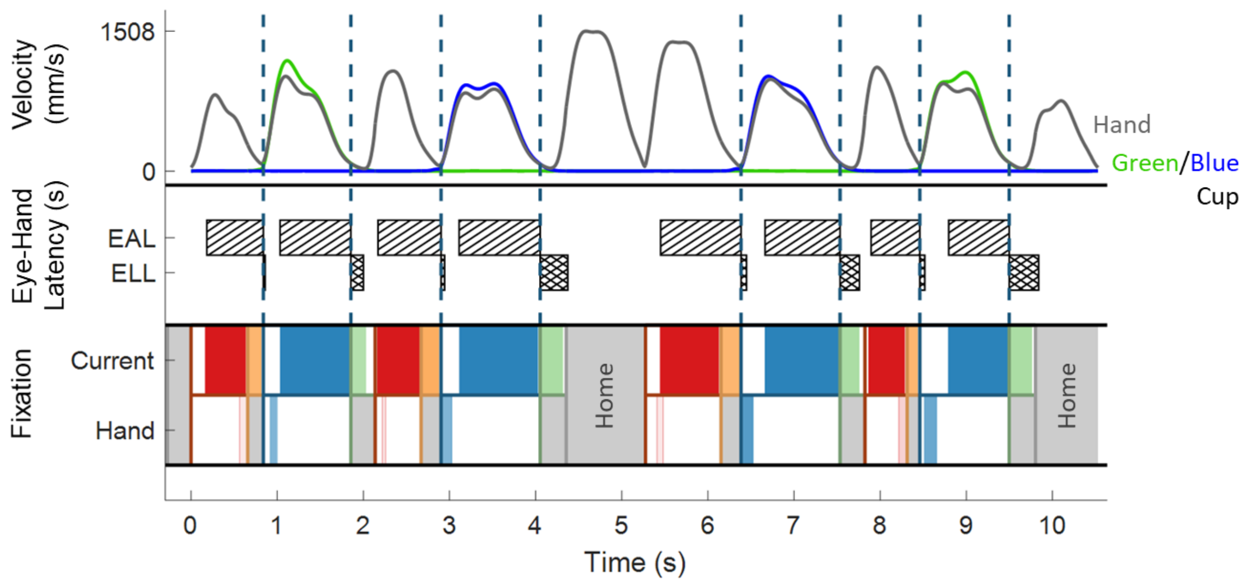
Appendix C. Detailed Report for Participant P14

Table C.1: Participant Information

Age (years)	55
Gender	Male
Level of amputation	Transradial
Amputation side	Left
Length of residual limb (cm)	12
Years since amputation at date of testing	26
Type of prosthesis	Body powered
Type of end-effector	Split hook, voluntary open
Hours per day of use	8
AM-ULA	21.7
UEFS	70.2

C.1 Cup Transfer Task Outcomes

Normative Data Set:



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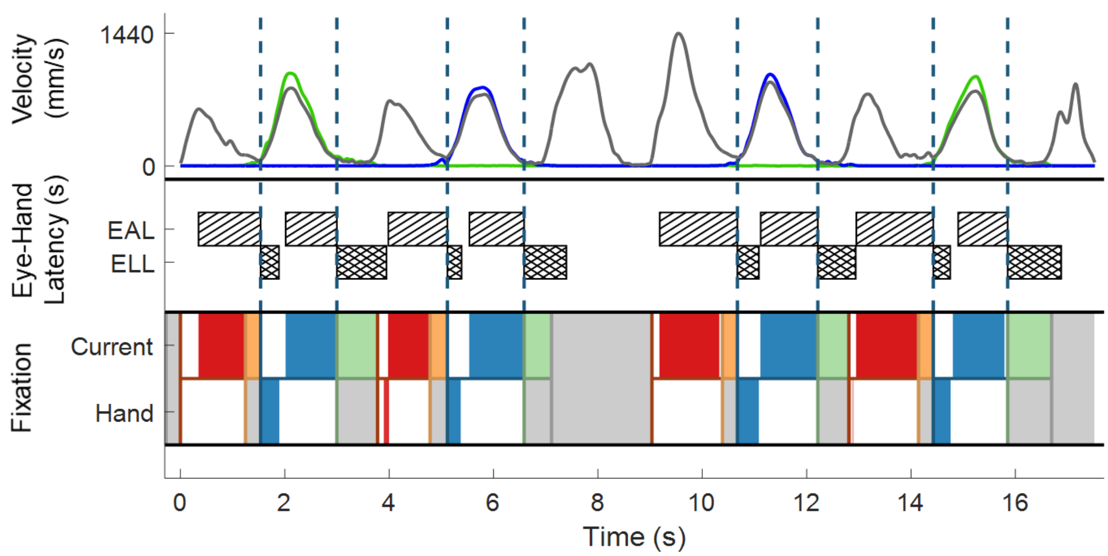


Figure C.1: Summary figures for prosthesis user participant compared with normative data. Top row: velocity plots for hand (grey) and objects (green cup and blue cup). Middle row: Eye Arrival Latencies and Eye Leaving Latencies (at Pick-Up and Drop-Off). Bottom row: fixation plots representing Percent Fixations to 'Current' and 'Hand Only' AOIs throughout each task phase: Reach (red), Grasp (orange), Transport (blue), and Release (green). Opacity level of fixation plots represents probability of fixation. The entire task is plotted with time along the x-axis.

Table C.2: Task performance

Number of successful trials	7
Trial success rate (%)	70%
Errors	2 - Incorrect movement sequence
	1 - Bead spillage
Number of trials analyzed	7

Table C.3: Phase Durations and Relative Phase Durations*

		Duration (s)				Relative Phase Duration (%)			
		Norm	SD	P14	SD	Norm	SD	P14	SD
M 1	R	0.66	0.09	1.25	0.22	30.79	1.72	33.29	5.68
	G	0.18	0.05	0.29	0.12	8.38	1.83	7.60	2.75
	T	1.02	0.10	1.46	0.23	47.77	2.42	38.85	5.37
	RL	0.28	0.07	0.78	0.40	13.06	2.34	20.26	8.36
M 2	R	0.53	0.09	1.01	0.07	24.00	1.67	30.29	2.35
	G	0.23	0.07	0.33	0.11	10.26	1.92	9.87	2.98
	T	1.15	0.12	1.47	0.23	52.15	2.72	44.00	4.44
	RL	0.30	0.07	0.52	0.16	13.59	2.88	15.84	4.83
M 3	R	0.88	0.12	1.35	0.12	34.43	2.03	35.78	2.76
	G	0.23	0.06	0.29	0.08	9.06	1.57	7.60	1.96
	T	1.15	0.12	1.54	0.05	45.30	2.42	40.87	1.67
	RL	0.29	0.09	0.59	0.08	11.21	3.00	15.75	2.27
M 4	R	0.49	0.06	1.34	0.24	24.91	2.60	34.27	4.38
	G	0.15	0.05	0.28	0.07	7.29	1.71	7.41	2.28
	T	1.04	0.12	1.43	0.24	52.57	2.65	36.69	5.14
	RL	0.31	0.09	0.84	0.15	15.23	3.74	21.63	3.39
	Total	10.53	1.32	17.52	1.09				

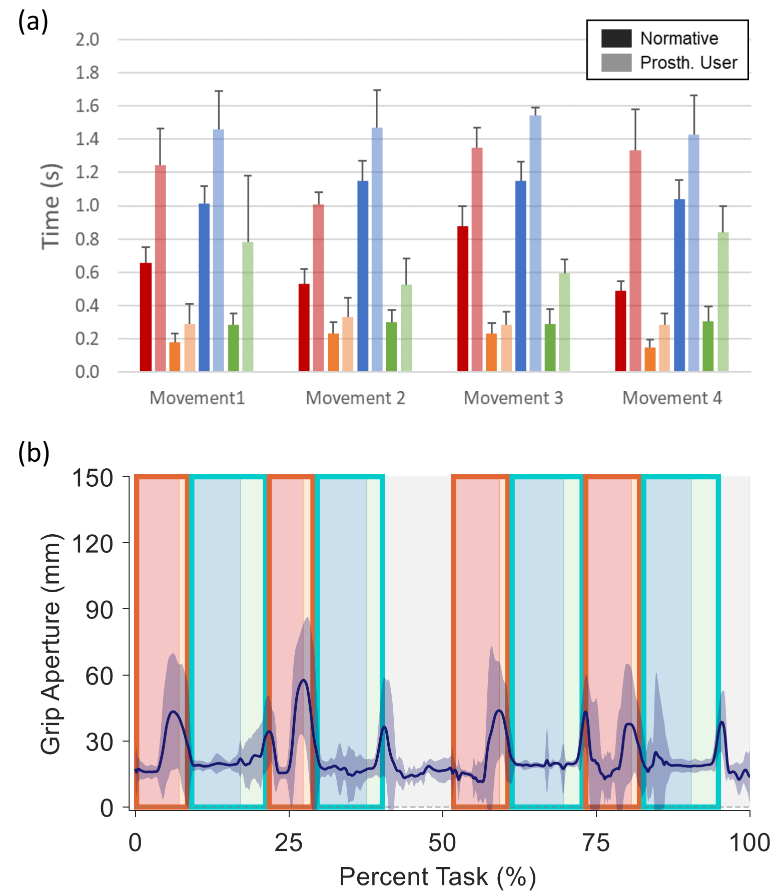


Figure C.2: (a) Phase Durations compared with normative data, (b) Grip Aperture profile. Phases are color coded: Reach (red), Grasp (orange), Transport(blue), and Release (green).

* For all tables: standard deviations are presented as between-participant SD for normative data and between-trial SD for prosthesis user participant data unless otherwise stated. Red highlighted cells indicate prosthesis user outcomes which were more than two SD from the normative mean.
M = Movement, R = Reach, G = Grasp, T = Transport, RL = Release.

Table C.4: Eye Gaze Fixation and Eye-Hand Latency Metrics*

		Mean Percent Fixations (When Fixated) (%)								Mean Number of Fixations							
		Current AOI				Hand Only AOI				Current AOI				Hand Only AOI			
		Norm	SD	P14	SD	Norm	SD	P14	SD	Norm	SD	P14	SD	Norm	SD	P14	SD
M 1	R	71.8	14.6	72.7	8.3	14.3	6.7	0.0	0.0	1.00	0.11	1.00	0.00	0.02	0.04	0.00	0.00
	G	82.5	21.3	100.0	0.0					0.89	0.16	1.00	0.00				
	T	78.8	11.4	66.9	3.1	8.2	4.8	23.6	6.6	1.02	0.03	1.00	0.00	0.52	0.32	1.00	0.00
	RL	58.0	18.2	100.0	0.0					0.87	0.18	1.00	0.00				
M 2	R	92.6	7.4	79.1	7.1	7.5	4.2	9.2	12.5	1.01	0.02	1.00	0.00	0.08	0.09	0.86	0.38
	G	86.7	13.9	100.0	0.0					0.95	0.10	1.00	0.00				
	T	79.5	11.9	70.7	8.2	10.3	4.0	17.3	7.7	1.01	0.02	1.00	0.00	0.58	0.29	1.00	0.00
	RL	82.2	16.7	100.0	0.0					0.94	0.22	1.00	0.00				
M 3	R	77.6	15.3	85.7	16.6	7.3	4.8	0.0	0.0	1.00	0.07	1.43	0.53	0.07	0.17	0.00	0.00
	G	90.4	14.5	100.0	0.0					0.90	0.24	1.00	0.00				
	T	74.5	10.7	70.5	8.2	11.8	6.1	26.5	4.6	1.03	0.05	1.14	0.38	0.74	0.33	1.00	0.00
	RL	75.7	15.3	100.0	0.0					0.94	0.15	1.00	0.00				
M 4	R	85.3	12.1	89.7	7.5	16.8	12.2	7.0	0.0	0.96	0.09	1.00	0.00	0.11	0.18	0.14	0.38
	G	78.1	21.9	100.0	0.0					0.83	0.27	1.00	0.00				
	T	66.2	14.6	69.1	8.2	13.7	9.6	22.5	4.6	0.96	0.14	1.14	0.38	0.68	0.43	1.00	0.00
	RL	82.5	18.9	100.0	0.0					0.94	0.17	1.00	0.00				

		EAL_{Grasp} (s)				EAL (s)				ELL (s)				$ELL_{Release}$ (s)			
		Norm	SD	P14	SD	Norm	SD	P14	SD	Norm	SD	P14	SD	Norm	SD	P14	SD
M 1	P	0.475	0.138	0.899	0.137	0.656	0.155	1.189	0.209	-0.020	0.103	-0.351	0.133				
	D					0.822	0.151	0.980	0.178	-0.146	0.101	-0.950	0.355	0.136	0.089	-0.169	0.049
M 2	P	0.500	0.104	0.800	0.125	0.732	0.165	1.131	0.188	-0.040	0.097	-0.273	0.123				
	D					0.941	0.119	1.048	0.251	-0.320	0.258	-0.811	0.217	-0.018	0.251	-0.286	0.092
M 3	P	0.700	0.153	1.201	0.196	0.934	0.185	1.488	0.220	-0.062	0.181	-0.412	0.070				
	D					0.870	0.160	1.094	0.122	-0.224	0.114	-0.725	0.153	0.065	0.110	-0.131	0.123
M 4	P	0.418	0.091	1.192	0.211	0.566	0.102	1.474	0.201	-0.057	0.193	-0.325	0.100				
	D					0.703	0.173	0.948	0.252	-0.341	0.190	-1.026	0.143	-0.036	0.174	-0.185	0.026

* For all tables: standard deviations are presented as between-participant SD for normative data and between-trial SD for prosthesis user participant data unless otherwise stated. Red highlighted cells indicate prosthesis user outcomes which were more than two SD from the normative mean.
M = Movement, R = Reach, G = Grasp, T = Transport, RL = Release, P = Pick-up, D = Drop-off.

Table C.5: End Effector Metrics*

		Hand Distance Travelled (mm)					Hand Trajectory Variability (mm)				Number of Movement Units				
		Norm	$SD_{b/n}$	$SD_{w/in}$	P14	SD	Norm	$SD_{b/n}$	P14	SD	Norm	$SD_{b/n}$	$SD_{w/in}$	P14	SD
M 1	R-G	366	52	23	459	135	16	3	41		1	0	0	4	1
	T-RL	646	39	21	671	25	17	4	37		2	0	1	6	2
M 2	R-G	456	56	30	529	31	17	4	22		1	0	0	3	1
	T-RL	700	46	27	670	18	20	5	25		2	0	1	4	1
M 3	R-G	887	35	25	1018	68	26	5	39		2	0	0	3	1
	T-RL	724	46	28	717	31	20	4	21		2	1	1	3	1
M 4	R-G	428	49	24	561	26	14	4	46		1	0	0	6	2
	T-RL	657	46	25	687	44	20	4	36		2	0	1	5	1

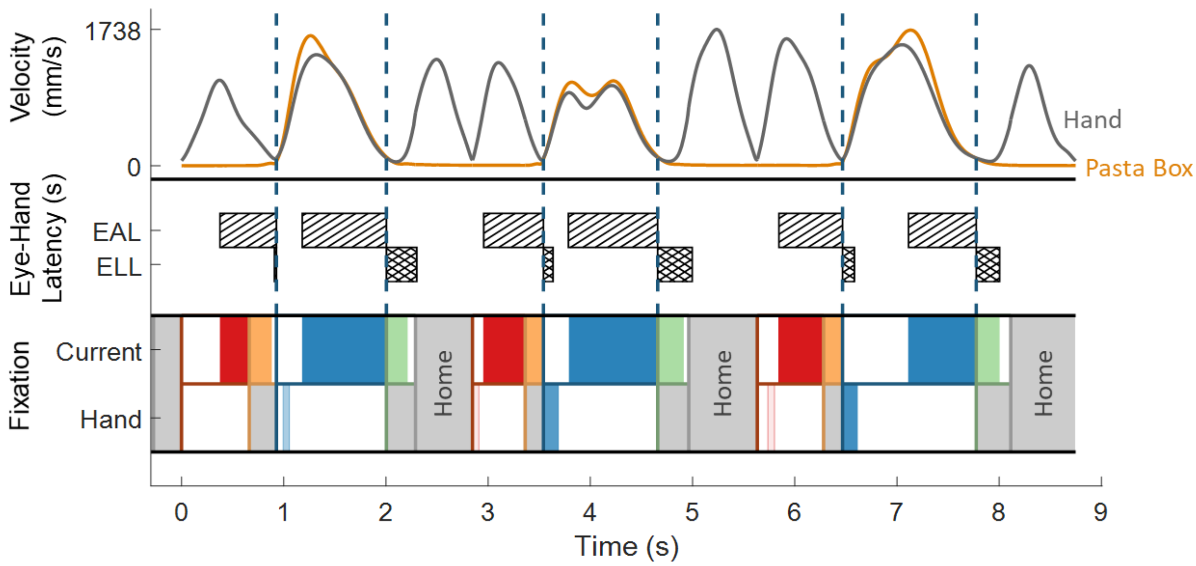
		Peak Hand Velocity (mm/s)					Percent to Peak Hand Velocity (%)				
		Norm	$SD_{b/n}$	$SD_{w/in}$	P14	SD	Norm	$SD_{b/n}$	$SD_{w/in}$	P14	SD
M 1	R-G	866	166	71	680	89	35.2	4.4	4.8	27.0	9.2
	T-RL	1042	88	52	874	117	21.0	2.6	3.0	24.9	3.0
M 2	R-G	1149	139	75	753	20	30.3	7.2	5.9	24.0	8.7
	T-RL	940	70	49	803	67	37.7	9.1	7.0	34.6	5.4
M 3	R-G	1492	187	82	1486	235	36.3	8.4	6.9	32.0	4.0
	T-RL	1009	56	52	923	58	24.7	2.4	2.8	29.1	2.7
M 4	R-G	1157	147	72	915	107	24.5	4.7	5.4	21.5	6.2
	T-RL	979	76	49	852	74	28.0	7.6	8.4	36.2	4.2

		Percent to Peak Hand Deceleration (%)					Percent to Peak Grip Aperture (%)					Peak Grip Aperture (mm)				
		Norm	$SD_{b/n}$	$SD_{w/in}$	P14	SD	Norm	$SD_{b/n}$	$SD_{w/in}$	P14	SD	Norm	$SD_{b/n}$	$SD_{w/in}$	P14	SD
M 1	R-G	62.0	8.7	13.7	48.7	8.8	80.4	4.7	5.1	77.3	15.3	99	4	3	46	11
M 2	R-G	49.8	6.5	6.9	40.6	17.7	73.0	6.3	9.1	77.6	9.8	114	6	4	58	12
M 3	R-G	61.0	5.3	5.9	51.8	11.8	80.4	3.9	4.9	82.3	6.3	114	7	2	44	11
M 4	R-G	62.3	13.5	11.8	43.3	11.9	83.7	5.4	9.2	82.0	11.7	100	5	4	40	13

* For all tables: standard deviations are presented as between-participant SD for normative data and between-trial SD for prosthesis user participant data unless otherwise stated. Red highlighted cells indicate prosthesis user outcomes which were more than two SD from the normative mean.
M = Movement, R = Reach, G = Grasp, T = Transport, RL = Release.

C.2 Pasta Box Task Outcomes

Normative Data Set:



P14:

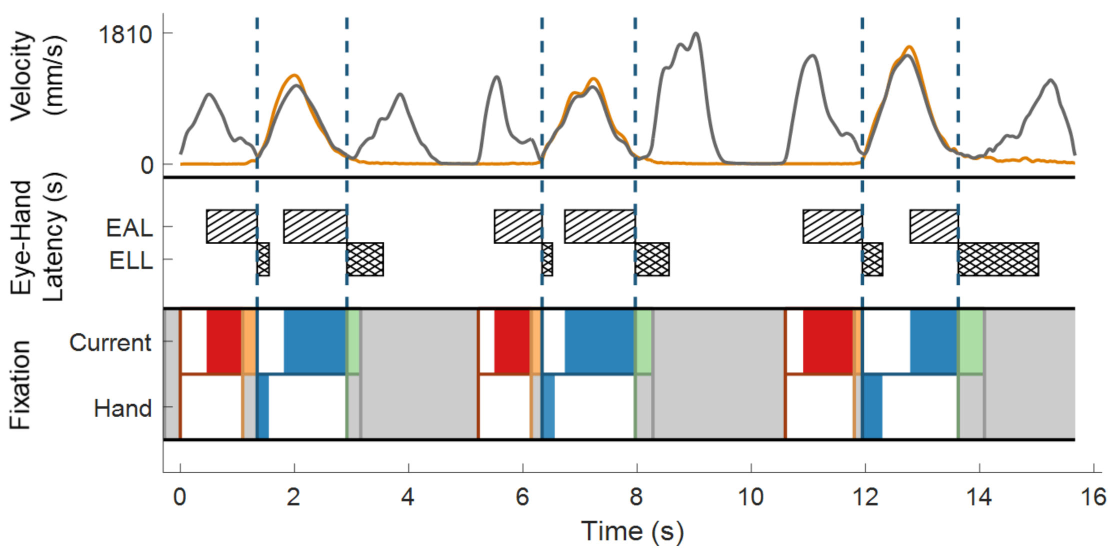


Figure C.3: Summary figures for prosthesis user participant compared with normative data. Top row: velocity plots for hand (grey) and objects (green cup and blue cup). Middle row: Eye Arrival Latencies and Eye Leaving Latencies (at Pick-Up and Drop-Off). Bottom row: fixation plots representing Percent Fixations to 'Current' and 'Hand Only' AOIs throughout each task phase: Reach (red), Grasp (orange), Transport (blue), and Release (green). Opacity level of fixation plots represents probability of fixation. The entire task is plotted with time along the x-axis.

Table C.6: Task performance

Number of successful trials	10
Trial success rate (%)	100%
Errors	N/A
Number of trials analyzed	10

Table C.7: Phase Durations and Relative Phase Durations*

		Duration (s)				Relative Phase Duration (%)			
		Norm	SD	P14	SD	Norm	SD	P14	SD
M 1	R	0.66	0.08	1.09	0.18	29.03	2.01	34.39	3.23
	G	0.27	0.08	0.25	0.14	11.47	2.47	7.83	3.49
	T	1.08	0.12	1.57	0.10	47.13	2.22	49.97	3.13
	RL	0.28	0.07	0.24	0.08	12.37	2.34	7.82	2.96
M 2	R	0.52	0.06	0.93	0.14	24.44	2.01	30.23	2.91
	G	0.18	0.05	0.19	0.02	8.32	1.67	6.20	0.79
	T	1.12	0.13	1.63	0.17	53.00	2.89	53.34	3.23
	RL	0.30	0.08	0.31	0.08	14.24	2.73	10.23	3.02
M 3	R	0.65	0.10	1.21	0.10	26.18	1.82	34.81	3.53
	G	0.19	0.06	0.14	0.05	7.36	1.78	4.04	1.39
	T	1.31	0.16	1.68	0.16	52.91	2.07	48.39	4.82
	RL	0.34	0.07	0.46	0.29	13.56	2.16	12.76	7.28
Total		8.75	1.20	15.67	0.85				

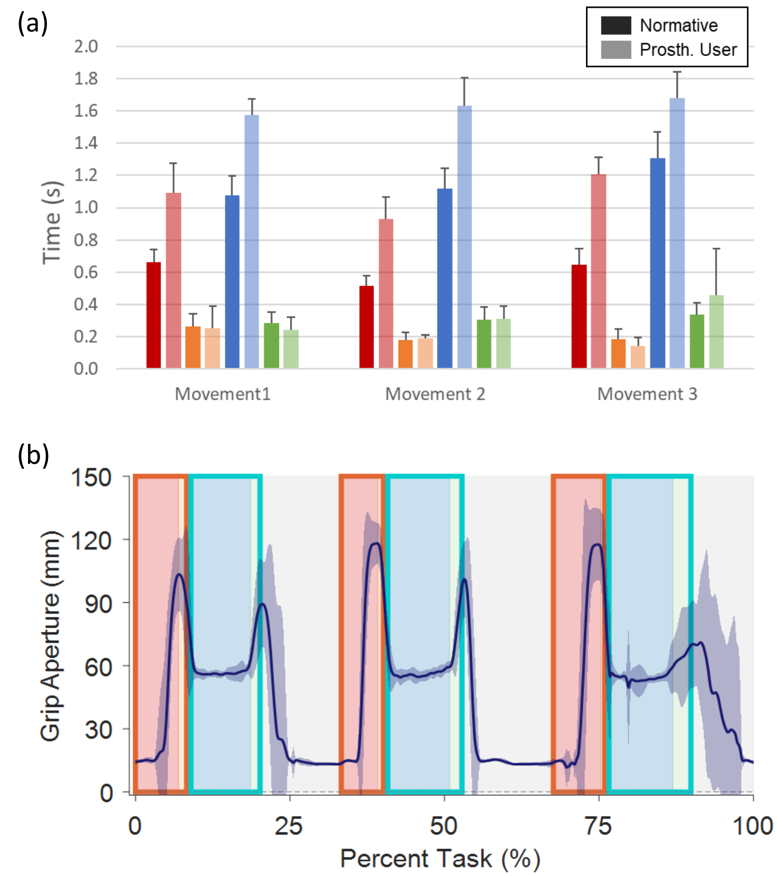


Figure C.4: (a) Phase Durations compared with normative data, (b) Grip Aperture profile. Phases are color coded: Reach (red), Grasp (orange), Transport(blue), and Release (green).

* For all tables: standard deviations are presented as between-participant SD for normative data and between-trial SD for prosthesis user participant data unless otherwise stated. Red highlighted cells indicate prosthesis user outcomes which were more than two SD from the normative mean.
M = Movement, R = Reach, G = Grasp, T = Transport, RL = Release.

Table C.8: Eye Gaze Fixation and Eye-Hand Latency Metrics*

		Mean Percent Fixations (When Fixated) (%)								Mean Number of Fixations							
		Current AOI				Hand Only AOI				Current AOI				Hand Only AOI			
		Norm	SD	P14	SD	Norm	SD	P14	SD	Norm	SD	P14	SD	Norm	SD	P14	SD
M 1	R	42.8	8.6	57.2	3.1	0.0	0.0	0.0	0.0	1.01	0.14	1.00	0.00	0.00	0.00	0.00	0.00
	G	82.7	15.0	100.0	0.0					0.97	0.07	1.00	0.00				
	T	75.1	9.7	70.1	8.3	5.8	2.4	12.7	5.9	1.03	0.05	1.00	0.00	0.32	0.33	1.00	0.00
	RL	71.8	18.0	100.0	0.0					0.99	0.03	1.00	0.00				
M 2	R	77.5	15.0	67.8	17.6	10.5	9.0	0.0	0.0	1.00	0.02	1.00	0.00	0.03	0.10	0.00	0.00
	G	89.4	15.3	100.0	0.0					0.93	0.15	0.90	0.32				
	T	76.9	9.3	75.2	7.3	12.7	6.7	13.0	3.6	1.02	0.06	1.00	0.00	0.75	0.28	0.90	0.32
	RL	81.8	15.1	100.0	0.0					0.99	0.03	1.00	0.00				
M 3	R	66.4	15.8	73.7	11.8	10.5	7.7	0.0	0.0	1.02	0.04	1.00	0.00	0.07	0.19	0.00	0.00
	G	93.6	14.0	100.0	0.0					0.98	0.05	1.00	0.00				
	T	50.0	4.7	50.0	4.5	11.2	3.6	20.8	5.3	1.06	0.09	1.00	0.00	0.85	0.27	1.10	0.32
	RL	64.2	15.8	100.0	0.0					1.00	0.09	1.00	0.00				

		EAL_{Grasp} (s)				EAL (s)				ELL (s)				$ELL_{Release}$ (s)			
		Norm	SD	P14	SD	Norm	SD	P14	SD	Norm	SD	P14	SD	Norm	SD	P14	SD
M 1	P	0.286	0.068	0.629	0.129	0.552	0.114	0.882	0.225	0.019	0.078	-0.209	0.086				
	D					0.823	0.200	1.103	0.153	-0.297	0.201	-0.635	0.190	-0.013	0.188	-0.393	0.140
M 2	P	0.405	0.106	0.642	0.246	0.584	0.141	0.831	0.247	-0.094	0.129	-0.180	0.150				
	D					0.873	0.171	1.233	0.211	-0.338	0.188	-0.591	0.097	-0.034	0.168	-0.281	0.076
M 3	P	0.437	0.134	0.890	0.162	0.623	0.174	1.032	0.176	-0.116	0.091	-0.354	0.109				
	D					0.662	0.100	0.840	0.118	-0.229	0.095	-1.404	0.451	0.109	0.065	-0.946	0.589

* For all tables: standard deviations are presented as between-participant SD for normative data and between-trial SD for prosthesis user participant data unless otherwise stated. Red highlighted cells indicate prosthesis user outcomes which were more than two SD from the normative mean.
M = Movement, R = Reach, G = Grasp, T = Transport, RL = Release, P = Pick-up, D = Drop-off.

Table C.9: End Effector Metrics*

		Hand Distance Travelled (mm)					Hand Trajectory Variability (mm)				Number of Movement Units				
		Norm	SDb/n	SDw/in	P14	SD	Norm	SDb/n	P14	SD	Norm	SDb/n	SDw/in	P14	SD
M 1	R-G	492	26	23	690	45	19	5	54		1	0	0	4	1
	T-RL	935	27	16	960	28	22	4	36		1	0	0	3	1
M 2	R-G	505	23	19	585	26	15	5	25		1	0	0	3	1
	T-RL	802	61	24	1019	50	20	4	38		2	0	0	4	2
M 3	R-G	746	24	14	1009	44	19	4	28		1	0	0	3	1
	T-RL	1186	31	18	1340	29	35	8	80		2	0	1	4	1

		Peak Hand Velocity (mm/s)					Percent to Peak Hand Velocity (%)				
		Norm	SDb/n	SDw/in	P14	SD	Norm	SDb/n	SDw/in	P14	SD
M 1	R-G	1164	163	90	1040	101	41.2	4.5	3.0	34.7	8.6
	T-RL	1447	136	81	1103	108	29.3	3.1	3.0	36.9	3.8
M 2	R-G	1352	191	64	1223	148	36.8	4.4	3.5	29.5	2.4
	T-RL	1069	112	55	1126	93	44.8	8.6	10.5	46.9	4.6
M 3	R-G	1666	261	92	1539	119	35.5	4.0	3.6	34.6	4.8
	T-RL	1598	180	106	1564	113	36.2	3.8	3.8	38.3	4.6

		Percent to Peak Hand Deceleration (%)					Percent to Peak Grip Aperture (%)					Peak Grip Aperture (mm)				
		Norm	SDb/n	SDw/in	P14	SD	Norm	SDb/n	SDw/in	P14	SD	Norm	SDb/n	SDw/in	P14	SD
M 1	R-G	55.7	8.0	7.8	74.5	17.5	73.3	6.5	6.9	85.4	6.3	116	8	8	104	9
M 2	R-G	72.6	8.6	5.6	45.9	16.8	80.1	8.0	4.6	74.1	9.6	106	10	5	119	4
M 3	R-G	72.8	8.4	5.9	46.3	3.5	81.5	4.9	5.0	82.9	7.8	109	8	5	118	8

* For all tables: standard deviations are presented as between-participant SD for normative data and between-trial SD for prosthesis user participant data unless otherwise stated. Red highlighted cells indicate prosthesis user outcomes which were more than two SD from the normative mean.
M = Movement, R = Reach, G = Grasp, T = Transport, RL = Release.

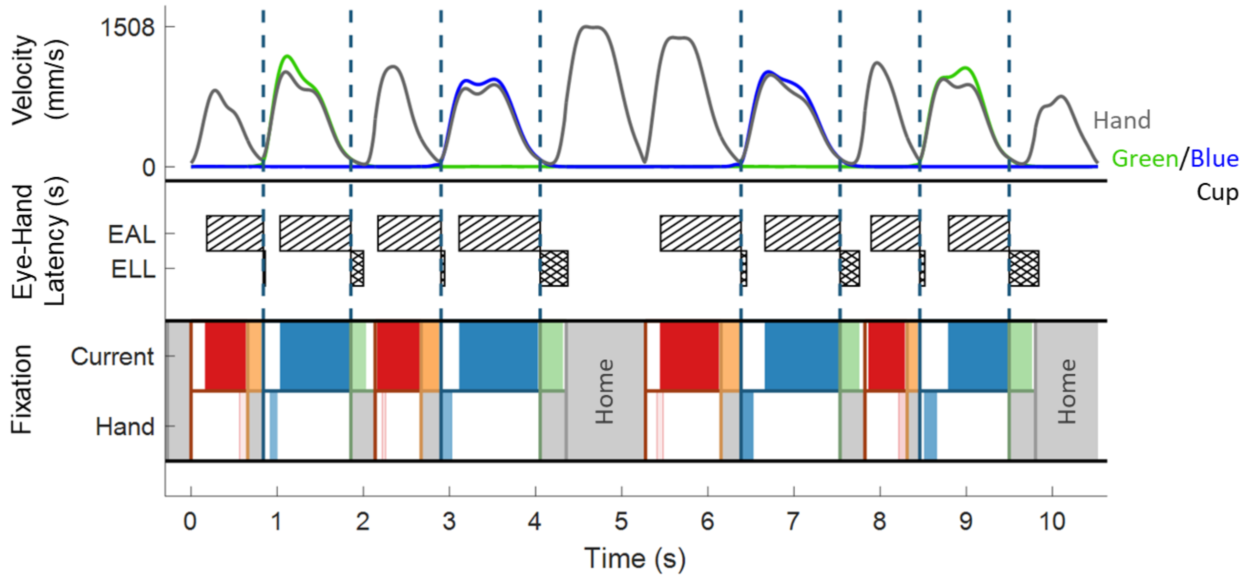
Appendix D. Detailed Report for Participant P85

Table D.1: Participant Information

Age (years)	45
Gender	Male
Level of amputation	Transradial
Amputation side	Right
Length of residual limb (cm)	11.5
Years since amputation at date of testing	10
Type of prosthesis	Body powered
Type of end-effector	Split hook, voluntary open
Hours per day of use	12
AM-ULA	20
UEFS	59.1

D.1 Cup Transfer Task Outcomes

Normative Data Set:



P85:

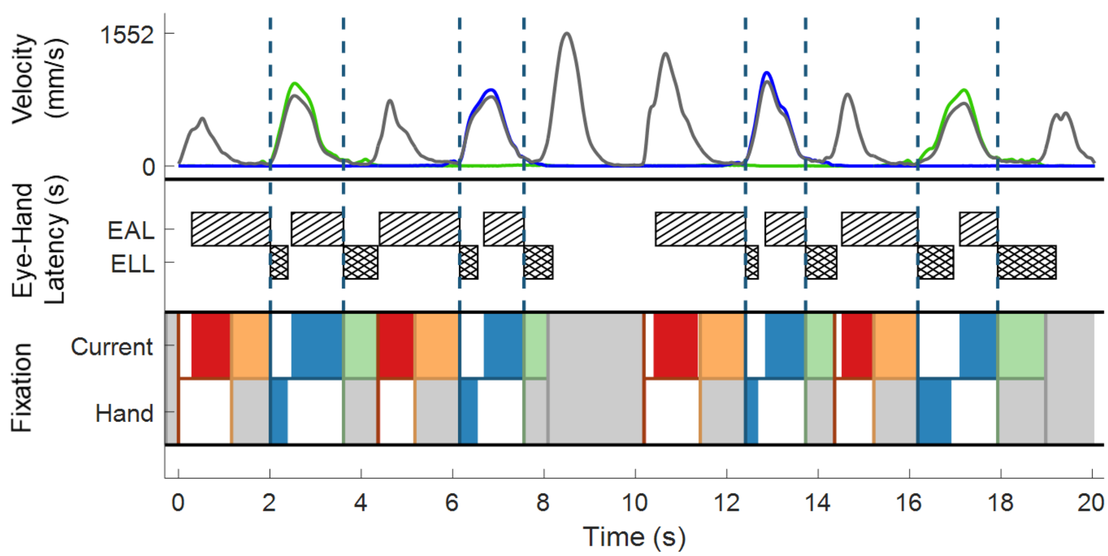


Figure D.1: Summary figures for prosthesis user participant compared with normative data. Top row: velocity plots for hand (grey) and objects (green cup and blue cup). Middle row: Eye Arrival Latencies and Eye Leaving Latencies (at Pick-Up and Drop-Off). Bottom row: fixation plots representing Percent Fixations to ‘Current’ and ‘Hand Only’ AOIs throughout each task phase: Reach (red), Grasp (orange), Transport (blue), and Release (green). Opacity level of fixation plots represents probability of fixation. The entire task is plotted with time along the x-axis.

Table D.2: Task performance

Number of successful trials	9
Trial success rate (%)	90%
Errors	1 – Hit partition
Number of trials analyzed	9

Table D.3: Phase Durations and Relative Phase Durations*

		Duration (s)				Relative Phase Duration (%)			
		Norm	SD	P85	SD	Norm	SD	P85	SD
M 1	R	0.66	0.09	1.16	0.03	30.79	1.72	26.68	1.66
	G	0.18	0.05	0.85	0.09	8.38	1.83	19.46	0.85
	T	1.02	0.10	1.60	0.12	47.77	2.42	36.67	2.33
	RL	0.28	0.07	0.75	0.16	13.06	2.34	17.19	2.70
M 2	R	0.53	0.09	0.81	0.09	24.00	1.67	21.81	2.41
	G	0.23	0.07	0.98	0.34	10.26	1.92	25.91	6.54
	T	1.15	0.12	1.41	0.18	52.15	2.72	38.17	6.16
	RL	0.30	0.07	0.53	0.18	13.59	2.88	14.11	4.43
M 3	R	0.88	0.12	1.23	0.11	34.43	2.03	29.74	3.88
	G	0.23	0.06	0.99	0.18	9.06	1.57	23.64	3.47
	T	1.15	0.12	1.31	0.18	45.30	2.42	31.59	4.16
	RL	0.29	0.09	0.64	0.32	11.21	3.00	15.02	6.66
M 4	R	0.49	0.06	0.86	0.05	24.91	2.60	18.86	3.02
	G	0.15	0.05	0.96	0.27	7.29	1.71	20.71	4.74
	T	1.04	0.12	1.75	0.24	52.57	2.65	37.90	3.71
	RL	0.31	0.09	1.05	0.27	15.23	3.74	22.52	4.32
Total		10.53	1.32	20.05	1.14				

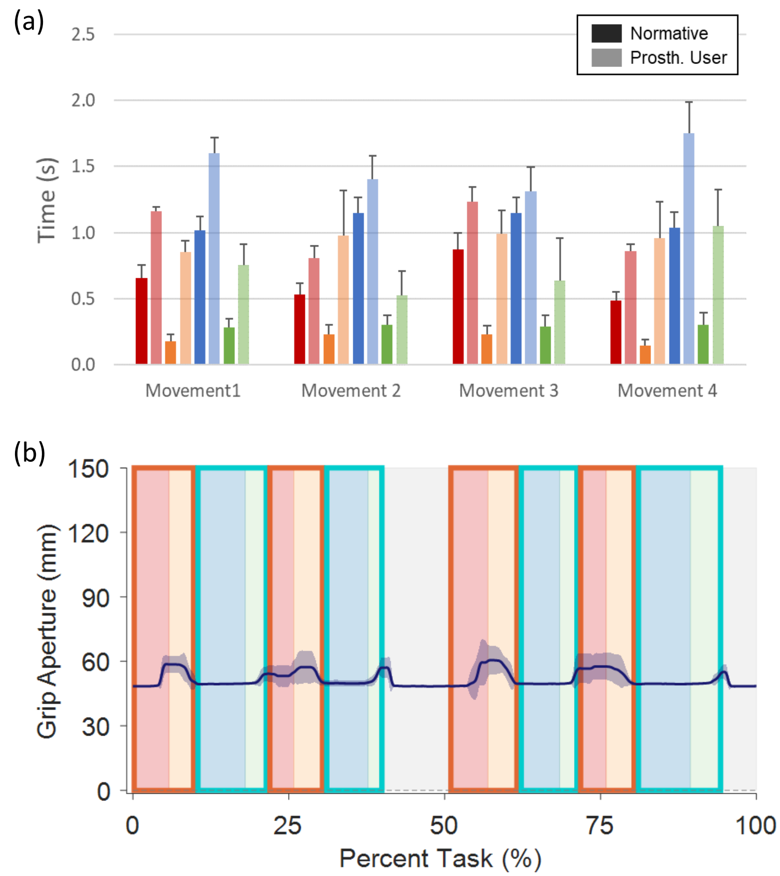


Figure D.2: (a) Phase Durations compared with normative data, (b) Grip Aperture profile. Phases are color coded: Reach (red), Grasp (orange), Transport(blue), and Release (green).

* For all tables: standard deviations are presented as between-participant SD for normative data and between-trial SD for prosthesis user participant data unless otherwise stated. Red highlighted cells indicate prosthesis user outcomes which were more than two SD from the normative mean.
M = Movement, R = Reach, G = Grasp, T = Transport, RL = Release.

Table D.4: Eye Gaze Fixation and Eye-Hand Latency Metrics*

		Mean Percent Fixations (When Fixated) (%)								Mean Number of Fixations							
		Current AOI				Hand Only AOI				Current AOI				Hand Only AOI			
		Norm	SD	P85	SD	Norm	SD	P85	SD	Norm	SD	P85	SD	Norm	SD	P85	SD
M 1	R	71.8	14.6	74.7	11.0	14.3	6.7	0.0	0.0	1.00	0.11	1.00	0.00	0.02	0.04	0.00	0.00
	G	82.5	21.3	100.0	0.0					0.89	0.16	1.00	0.00				
	T	78.8	11.4	71.1	5.5	8.2	4.8	23.6	6.5	1.02	0.03	1.11	0.33	0.52	0.32	1.00	0.00
	RL	58.0	18.2	97.8	2.3					0.87	0.18	1.00	0.00				
M 2	R	92.6	7.4	95.6	5.9	7.5	4.2	4.0	1.9	1.01	0.02	1.00	0.00	0.08	0.09	0.44	0.53
	G	86.7	13.9	100.0	0.0					0.95	0.10	1.00	0.00				
	T	79.5	11.9	63.0	8.2	10.3	4.0	27.2	9.7	1.01	0.02	1.00	0.00	0.58	0.29	1.00	0.00
	RL	82.2	16.7	99.8	0.7					0.94	0.22	1.00	0.00				
M 3	R	77.6	15.3	79.1	22.0	7.3	4.8	3.5	0.0	1.00	0.07	1.22	0.44	0.07	0.17	0.11	0.33
	G	90.4	14.5	99.2	2.5					0.90	0.24	1.00	0.00				
	T	74.5	10.7	66.8	5.1	11.8	6.1	20.2	2.1	1.03	0.05	1.00	0.00	0.74	0.33	1.00	0.00
	RL	75.7	15.3	90.3	29.2					0.94	0.15	1.00	0.00				
M 4	R	85.3	12.1	81.6	6.3	16.8	12.2	0.0	0.0	0.96	0.09	1.00	0.00	0.11	0.18	0.00	0.00
	G	78.1	21.9	100.0	0.0					0.83	0.27	1.00	0.00				
	T	66.2	14.6	47.7	4.5	13.7	9.6	41.0	7.1	0.96	0.14	1.00	0.00	0.68	0.43	1.33	0.71
	RL	82.5	18.9	98.3	5.2					0.94	0.17	1.00	0.00				

		EAL_{Grasp} (s)				EAL (s)				ELL (s)				$ELL_{Release}$ (s)			
		Norm	SD	P85	SD	Norm	SD	P85	SD	Norm	SD	P85	SD	Norm	SD	P85	SD
M 1	P	0.475	0.138	0.869	0.139	0.656	0.155	1.719	0.181	-0.020	0.103	-0.382	0.120				
	D					0.822	0.151	1.135	0.093	-0.146	0.101	-0.749	0.143	0.136	0.089	0.006	0.038
M 2	P	0.500	0.104	0.773	0.100	0.732	0.165	1.754	0.402	-0.040	0.097	-0.394	0.175				
	D					0.941	0.119	0.877	0.086	-0.320	0.258	-0.629	0.160	-0.018	0.251	-0.103	0.073
M 3	P	0.700	0.153	0.975	0.240	0.934	0.185	1.965	0.352	-0.062	0.181	-0.276	0.042				
	D					0.870	0.160	0.882	0.170	-0.224	0.114	-0.680	0.360	0.065	0.110	-0.045	0.137
M 4	P	0.418	0.091	0.699	0.061	0.566	0.102	1.661	0.251	-0.057	0.193	-0.780	0.239				
	D					0.703	0.173	0.828	0.089	-0.341	0.190	-1.274	0.439	-0.036	0.174	-0.224	0.284

* For all tables: standard deviations are presented as between-participant SD for normative data and between-trial SD for prosthesis user participant data unless otherwise stated. Red highlighted cells indicate prosthesis user outcomes which were more than two SD from the normative mean.
M = Movement, R = Reach, G = Grasp, T = Transport, RL = Release, P = Pick-up, D = Drop-off.

Table D.5: End Effector Metrics*

		Hand Distance Travelled (mm)					Hand Trajectory Variability (mm)				Number of Movement Units				
		Norm	SDb/n	SDw/in	P85	SD	Norm	SDb/n	P85	SD	Norm	SDb/n	SDw/in	P85	SD
M 1	R-G	366	52	23	385	37	16	3	22		1	0	0	6	2
	T-RL	646	39	21	688	19	17	4	30		2	0	1	6	2
M 2	R-G	456	56	30	443	36	17	4	21		1	0	0	5	2
	T-RL	700	46	27	729	28	20	5	47		2	0	1	4	2
M 3	R-G	887	35	25	961	65	26	5	56		2	0	0	6	1
	T-RL	724	46	28	713	24	20	4	33		2	1	1	5	2
M 4	R-G	428	49	24	432	18	14	4	20		1	0	0	6	2
	T-RL	657	46	25	677	36	20	4	42		2	0	1	8	2

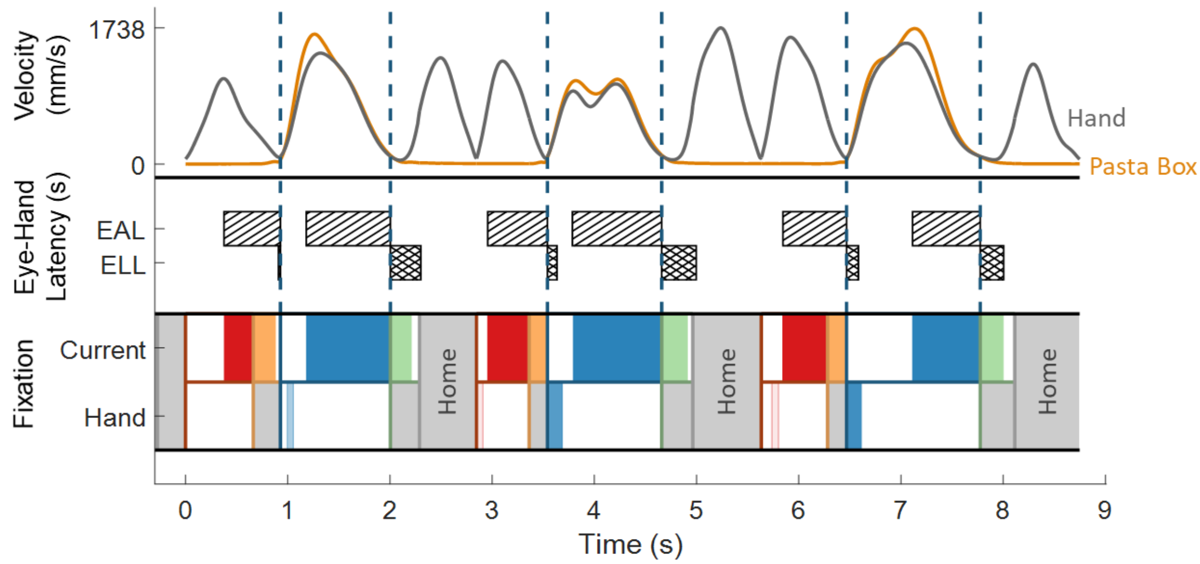
		Peak Hand Velocity (mm/s)					Percent to Peak Hand Velocity (%)				
		Norm	SDb/n	SDw/in	P85	SD	Norm	SDb/n	SDw/in	P85	SD
M 1	R-G	866	166	71	604	54	35.2	4.4	4.8	25.3	5.3
	T-RL	1042	88	52	847	68	21.0	2.6	3.0	21.6	2.8
M 2	R-G	1149	139	75	838	99	30.3	7.2	5.9	15.2	2.7
	T-RL	940	70	49	899	65	37.7	9.1	7.0	37.0	6.1
M 3	R-G	1492	187	82	1416	205	36.3	8.4	6.9	20.9	3.6
	T-RL	1009	56	52	1033	73	24.7	2.4	2.8	24.8	3.0
M 4	R-G	1157	147	72	869	72	24.5	4.7	5.4	17.1	2.9
	T-RL	979	76	49	783	60	28.0	7.6	8.4	37.4	3.8

		Percent to Peak Hand Deceleration (%)					Percent to Peak Grip Aperture (%)					Peak Grip Aperture (mm)				
		Norm	SDb/n	SDw/in	P85	SD	Norm	SDb/n	SDw/in	P85	SD	Norm	SDb/n	SDw/in	P85	SD
M 1	R-G	62.0	8.7	13.7	31.6	4.9	80.4	4.7	5.1	52.6	1.6	99	4	3	59	2
M 2	R-G	49.8	6.5	6.9	19.1	3.2	73.0	6.3	9.1	94.3	18.1	114	6	4	51	4
M 3	R-G	61.0	5.3	5.9	30.9	6.4	80.4	3.9	4.9	50.9	12.4	114	7	2	61	3
M 4	R-G	62.3	13.5	11.8	27.8	5.8	83.7	5.4	9.2	100.0	1.3	100	5	4	49	0

* For all tables: standard deviations are presented as between-participant SD for normative data and between-trial SD for prosthesis user participant data unless otherwise stated. Red highlighted cells indicate prosthesis user outcomes which were more than two SD from the normative mean.
M = Movement, R = Reach, G = Grasp, T = Transport, RL = Release.

D.2 Pasta Box Task Outcomes

Normative Data Set:



P85:

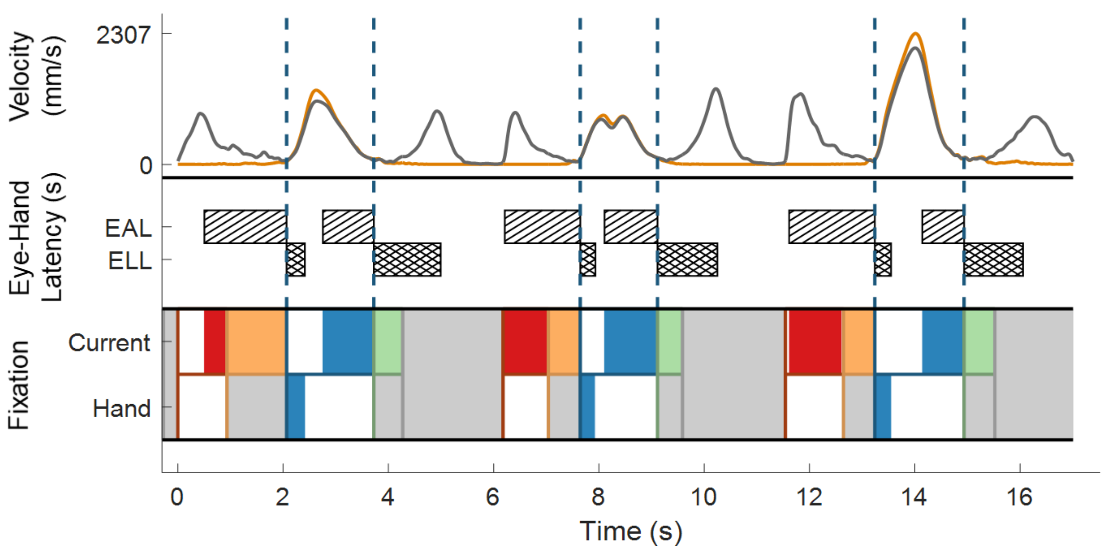


Figure D.3: Summary figures for prosthesis user participant compared with normative data. Top row: velocity plots for hand (grey) and objects (green cup and blue cup). Middle row: Eye Arrival Latencies and Eye Leaving Latencies (at Pick-Up and Drop-Off). Bottom row: fixation plots representing Percent Fixations to 'Current' and 'Hand Only' AOIs throughout each task phase: Reach (red), Grasp (orange), Transport (blue), and Release (green). Opacity level of fixation plots represents probability of fixation. The entire task is plotted with time along the x-axis.

Table D.6: Task performance

Number of successful trials	9
Trial success rate (%)	90%
Errors	1 – Movement hesitation
Number of trials analyzed	9

Table D.7: Phase Durations and Relative Phase Durations*

		Duration (s)				Relative Phase Duration (%)			
		Norm	SD	P85	SD	Norm	SD	P85	SD
M 1	R	0.66	0.08	0.93	0.08	29.03	2.01	22.41	3.62
	G	0.27	0.08	1.13	0.81	11.47	2.47	25.02	11.08
	T	1.08	0.12	1.66	0.31	47.13	2.22	39.69	7.80
	RL	0.28	0.07	0.55	0.17	12.37	2.34	12.88	3.52
M 2	R	0.52	0.06	0.86	0.11	24.44	2.01	25.32	3.24
	G	0.18	0.05	0.61	0.19	8.32	1.67	17.64	4.74
	T	1.12	0.13	1.47	0.12	53.00	2.89	43.20	4.35
	RL	0.30	0.08	0.47	0.17	14.24	2.73	13.84	4.48
M 3	R	0.65	0.10	1.10	0.15	26.18	1.82	27.97	4.87
	G	0.19	0.06	0.60	0.27	7.36	1.78	14.80	6.20
	T	1.31	0.16	1.70	0.23	52.91	2.07	42.70	5.76
	RL	0.34	0.07	0.58	0.23	13.56	2.16	14.53	5.28
Total		8.75	1.20	17.01	0.75				

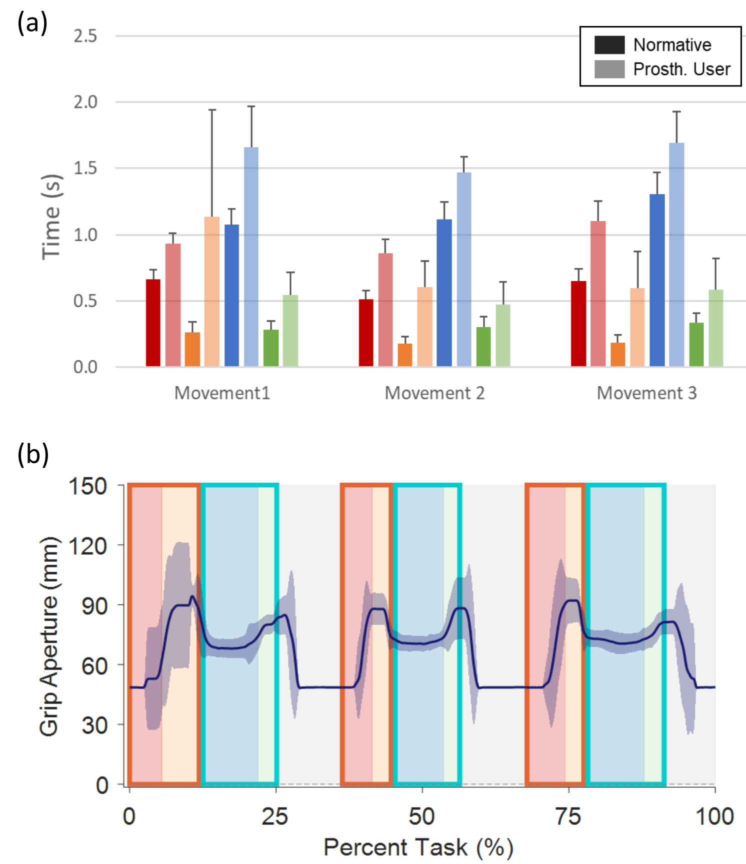


Figure D.4: (a) Phase Durations compared with normative data, (b) Grip Aperture profile. Phases are color coded: Reach (red), Grasp (orange), Transport(blue), and Release (green).

* For all tables: standard deviations are presented as between-participant SD for normative data and between-trial SD for prosthesis user participant data unless otherwise stated. Red highlighted cells indicate prosthesis user outcomes which were more than two SD from the normative mean.
M = Movement, R = Reach, G = Grasp, T = Transport, RL = Release.

Table D.8: Eye Gaze Fixation and Eye-Hand Latency Metrics*

		Mean Percent Fixations (When Fixated) (%)								Mean Number of Fixations							
		Current AOI				Hand Only AOI				Current AOI				Hand Only AOI			
		Norm	SD	P85	SD	Norm	SD	P85	SD	Norm	SD	P85	SD	Norm	SD	P85	SD
M 1	R	42.8	8.6	45.6	8.2	0.0	0.0	0.0	0.0	1.01	0.14	1.00	0.00	0.00	0.00	0.00	0.00
	G	82.7	15.0	100.0	0.0					0.97	0.07	1.00	0.00				
	T	75.1	9.7	58.0	4.7	5.8	2.4	20.6	6.7	1.03	0.05	1.00	0.00	0.32	0.33	1.00	0.00
	RL	71.8	18.0	100.0	0.0					0.99	0.03	1.00	0.00				
M 2	R	77.5	15.0	96.0	6.7	10.5	9.0	0.0	0.0	1.00	0.02	1.00	0.00	0.03	0.10	0.00	0.00
	G	89.4	15.3	100.0	0.0					0.93	0.15	1.00	0.00				
	T	76.9	9.3	67.7	4.5	12.7	6.7	19.0	6.5	1.02	0.06	1.11	0.33	0.75	0.28	1.00	0.00
	RL	81.8	15.1	100.0	0.0					0.99	0.03	1.00	0.00				
M 3	R	66.4	15.8	90.3	15.1	10.5	7.7	0.0	0.0	1.02	0.04	1.22	0.44	0.07	0.19	0.00	0.00
	G	93.6	14.0	100.0	0.0					0.98	0.05	1.00	0.00				
	T	50.0	4.7	46.4	5.5	11.2	3.6	18.1	5.5	1.06	0.09	1.00	0.00	0.85	0.27	1.00	0.00
	RL	64.2	15.8	100.0	0.0					1.00	0.09	1.00	0.00				

		EAL_{Grasp} (s)				EAL (s)				ELL (s)				$ELL_{Release}$ (s)			
		Norm	SD	P85	SD	Norm	SD	P85	SD	Norm	SD	P85	SD	Norm	SD	P85	SD
M 1	P	0.286	0.068	0.429	0.100	0.552	0.114	1.562	0.808	0.019	0.078	-0.346	0.130				
	D					0.823	0.200	0.969	0.240	-0.297	0.201	-1.269	0.467	-0.013	0.188	-0.721	0.468
M 2	P	0.405	0.106	0.827	0.116	0.584	0.141	1.433	0.199	-0.094	0.129	-0.289	0.113				
	D					0.873	0.171	1.006	0.105	-0.338	0.188	-1.138	0.731	-0.034	0.168	-0.664	0.607
M 3	P	0.437	0.134	1.032	0.198	0.623	0.174	1.628	0.203	-0.116	0.091	-0.308	0.107				
	D					0.662	0.100	0.793	0.200	-0.229	0.095	-1.121	0.443	0.109	0.065	-0.537	0.366

* For all tables: standard deviations are presented as between-participant SD for normative data and between-trial SD for prosthesis user participant data unless otherwise stated. Red highlighted cells indicate prosthesis user outcomes which were more than two SD from the normative mean.
M = Movement, R = Reach, G = Grasp, T = Transport, RL = Release, P = Pick-up, D = Drop-off.

Table D.9: End Effector Metrics*

Hand Distance Travelled (mm)

		Norm	$SD_{b/n}$	$SD_{w/in}$	P85	SD
M 1	R-G	492	26	23	675	238
	T-RL	935	27	16	960	28
M 2	R-G	505	23	19	474	32
	T-RL	802	61	24	834	27
M 3	R-G	746	24	14	785	35
	T-RL	1186	31	18	1719	57

Hand Trajectory Variability (mm)

		Norm	$SD_{b/n}$	P85	SD
M 1	R-G	19	5	48	
	T-RL	22	4	68	
M 2	R-G	15	5	26	
	T-RL	20	4	32	
M 3	R-G	19	4	34	
	T-RL	35	8	92	

Number of Movement Units

		Norm	$SD_{b/n}$	$SD_{w/in}$	P85	SD
M 1	R-G	1	0	0	8	3
	T-RL	1	0	0	6	2
M 2	R-G	1	0	0	5	2
	T-RL	2	0	0	5	1
M 3	R-G	1	0	0	7	2
	T-RL	2	0	1	6	2

Peak Hand Velocity (mm/s)

		Norm	$SD_{b/n}$	$SD_{w/in}$	P85	SD
M 1	R-G	1164	163	90	1054	118
	T-RL	1447	136	81	1213	77
M 2	R-G	1352	191	64	976	102
	T-RL	1069	112	55	879	56
M 3	R-G	1666	261	92	1276	203
	T-RL	1598	180	106	2113	169

Percent to Peak Hand Velocity (%)

		Norm	$SD_{b/n}$	$SD_{w/in}$	P85	SD
M 1	R-G	41.2	4.5	3.0	20.5	5.3
	T-RL	29.3	3.1	3.0	26.7	4.1
M 2	R-G	36.8	4.4	3.5	15.4	3.6
	T-RL	44.8	8.6	10.5	42.0	3.1
M 3	R-G	35.5	4.0	3.6	16.6	3.6
	T-RL	36.2	3.8	3.8	35.2	3.2

Percent to Peak Hand Deceleration (%)

		Norm	$SD_{b/n}$	$SD_{w/in}$	P85	SD
M 1	R-G	55.7	8.0	7.8	36.7	17.6
M 2	R-G	72.6	8.6	5.6	28.5	7.1
M 3	R-G	72.8	8.4	5.9	31.0	6.9

Percent to Peak Grip Aperture (%)

		Norm	$SD_{b/n}$	$SD_{w/in}$	P85	SD
M 1	R-G	73.3	6.5	6.9	79.6	15.6
M 2	R-G	80.1	8.0	4.6	73.0	13.5
M 3	R-G	81.5	4.9	5.0	74.0	17.7

Peak Grip Aperture (mm)

		Norm	$SD_{b/n}$	$SD_{w/in}$	P85	SD
M 1	R-G	116	8	8	95	3
M 2	R-G	106	10	5	88	4
M 3	R-G	109	8	5	93	5

* For all tables: standard deviations are presented as between-participant SD for normative data and between-trial SD for prosthesis user participant data unless otherwise stated. Red highlighted cells indicate prosthesis user outcomes which were more than two SD from the normative mean.

M = Movement, R = Reach, G = Grasp, T = Transport, RL = Release.

Appendix E. Detailed Report for Participant P50

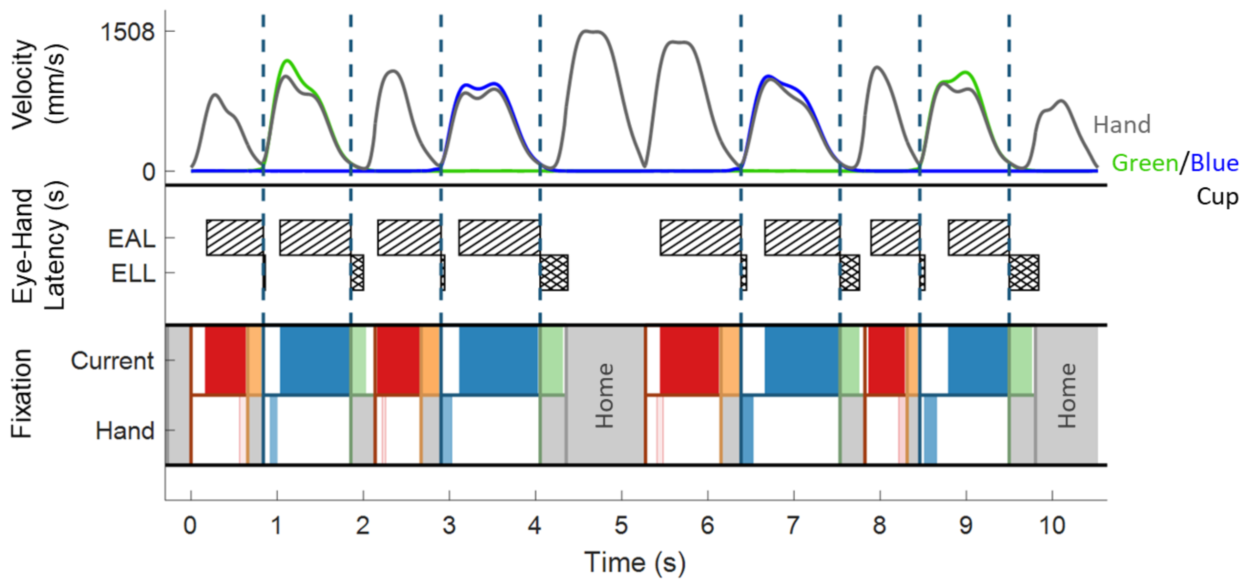
Table E.1: Participant Information

Age (years)	64
Gender	Male
Level of amputation	Transradial
Amputation side	Both[1]
Length of residual limb (cm)	Not recorded
Years since amputation at date of testing	12
Type of prosthesis	Body powered
Type of end-effector	Split hook, voluntary open
Hours per day of use	14
AM-ULA	17.8
UEFS	49.7

[1] Completed experimental tasks with right arm (side with transradial amputation)

E.1 Cup Transfer Task Outcomes

Normative Data Set:



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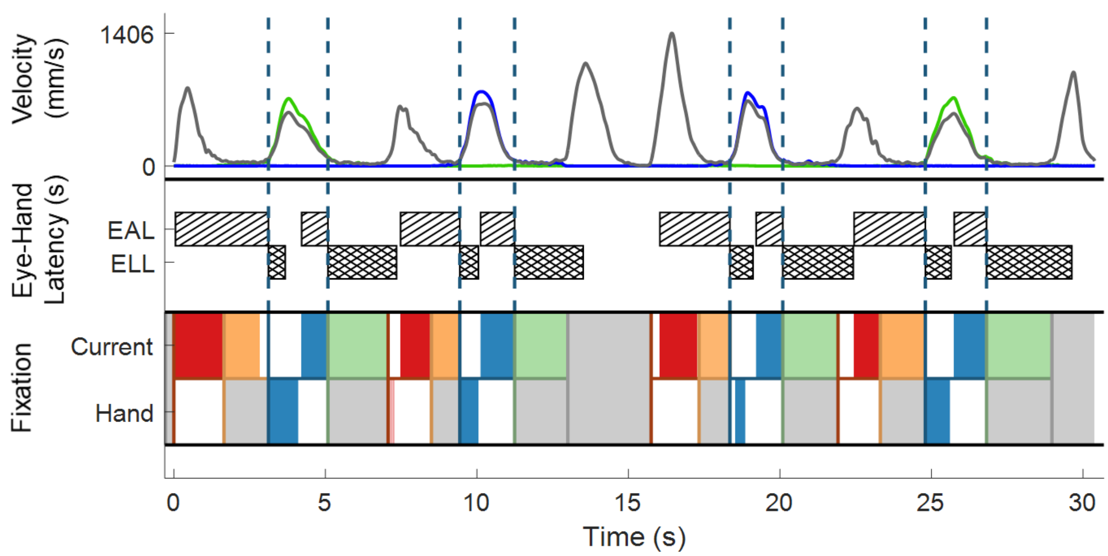


Figure E.1: Summary figures for prosthesis user participant compared with normative data. Top row: velocity plots for hand (grey) and objects (green cup and blue cup). Middle row: Eye Arrival Latencies and Eye Leaving Latencies (at Pick-Up and Drop-Off). Bottom row: fixation plots representing Percent Fixations to 'Current' and 'Hand Only' AOIs throughout each task phase: Reach (red), Grasp (orange), Transport (blue), and Release (green). Opacity level of fixation plots represents probability of fixation. The entire task is plotted with time along the x-axis.

Table E.2: Task performance

Number of successful trials	7
Trial success rate (%)	70%
Errors	2 – Movement hesitation
	1 – Undesired movement
Number of trials analyzed	7

Table E.3: Phase Durations and Relative Phase Durations*

		Duration (s)				Relative Phase Duration (%)			
		Norm	SD	P50	SD	Norm	SD	P50	SD
M 1	R	0.66	0.09	1.65	0.37	30.79	1.72	23.71	6.27
	G	0.18	0.05	1.47	0.64	8.38	1.83	20.28	7.54
	T	1.02	0.10	1.96	0.16	47.77	2.42	28.00	3.76
	RL	0.28	0.07	1.99	0.33	13.06	2.34	28.01	3.37
M 2	R	0.53	0.09	1.43	0.37	24.00	1.67	24.00	4.45
	G	0.23	0.07	0.94	0.22	10.26	1.92	15.91	3.94
	T	1.15	0.12	1.81	0.19	52.15	2.72	30.85	4.35
	RL	0.30	0.07	1.75	0.52	13.59	2.88	29.23	5.72
M 3	R	0.88	0.12	1.58	0.07	34.43	2.03	25.73	1.58
	G	0.23	0.06	1.02	0.25	9.06	1.57	16.34	2.91
	T	1.15	0.12	1.74	0.23	45.30	2.42	28.36	3.60
	RL	0.29	0.09	1.83	0.25	11.21	3.00	29.56	2.63
M 4	R	0.49	0.06	1.40	0.31	24.91	2.60	19.92	4.76
	G	0.15	0.05	1.49	0.33	7.29	1.71	20.99	3.76
	T	1.04	0.12	2.02	0.20	52.57	2.65	28.69	2.84
	RL	0.31	0.09	2.16	0.52	15.23	3.74	30.40	5.65
	Total	10.53	1.32	30.39	1.00				

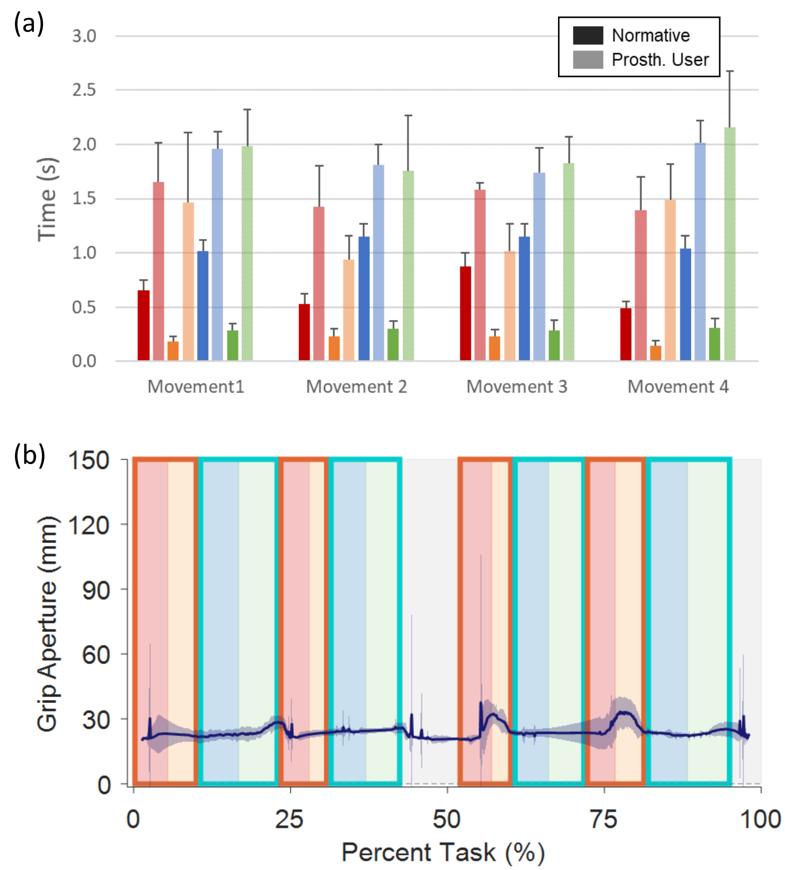


Figure E.2: (a) Phase Durations compared with normative data, (b) Grip Aperture profile. Phases are color coded: Reach (red), Grasp (orange), Transport(blue), and Release (green).

* For all tables: standard deviations are presented as between-participant SD for normative data and between-trial SD for prosthesis user participant data unless otherwise stated. Red highlighted cells indicate prosthesis user outcomes which were more than two SD from the normative mean.
M = Movement, R = Reach, G = Grasp, T = Transport, RL = Release.

Table E.4: Eye Gaze Fixation and Eye-Hand Latency Metrics*

		Mean Percent Fixations (When Fixated) (%)								Mean Number of Fixations							
		Current AOI				Hand Only AOI				Current AOI				Hand Only AOI			
		Norm	SD	P50	SD	Norm	SD	P50	SD	Norm	SD	P50	SD	Norm	SD	P50	SD
M 1	R	71.8	14.6	96.7	3.0	14.3	6.7	0.0	0.0	1.00	0.11	1.00	0.00	0.02	0.04	0.00	0.00
	G	82.5	21.3	86.0	36.9					0.89	0.16	1.00	0.00				
	T	78.8	11.4	44.3	3.2	8.2	4.8	48.4	6.9	1.02	0.03	1.00	0.00	0.52	0.32	1.14	0.38
	RL	58.0	18.2	100.0	0.0					0.87	0.18	1.00	0.00				
M 2	R	92.6	7.4	72.8	9.5	7.5	4.2	8.5	8.6	1.01	0.02	1.00	0.00	0.08	0.09	0.29	0.49
	G	86.7	13.9	100.0	0.0					0.95	0.10	1.00	0.00				
	T	79.5	11.9	62.7	13.1	10.3	4.0	32.6	12.6	1.01	0.02	1.00	0.00	0.58	0.29	1.00	0.00
	RL	82.2	16.7	100.0	0.0					0.94	0.22	1.00	0.00				
M 3	R	77.6	15.3	77.6	12.9	7.3	4.8	0.0	0.0	1.00	0.07	1.14	0.38	0.07	0.17	0.00	0.00
	G	90.4	14.5	100.0	0.0					0.90	0.24	0.86	0.38				
	T	74.5	10.7	50.5	5.7	11.8	6.1	18.4	8.5	1.03	0.05	1.00	0.00	0.74	0.33	1.86	0.69
	RL	75.7	15.3	100.0	0.0					0.94	0.15	1.00	0.00				
M 4	R	85.3	12.1	63.8	12.2	16.8	12.2	0.0	0.0	0.96	0.09	1.00	0.00	0.11	0.18	0.00	0.00
	G	78.1	21.9	100.0	0.0					0.83	0.27	1.00	0.00				
	T	66.2	14.6	53.0	4.0	13.7	9.6	40.1	6.9	0.96	0.14	1.00	0.00	0.68	0.43	1.14	0.38
	RL	82.5	18.9	100.0	0.0					0.94	0.17	1.00	0.00				

		EAL_{Grasp} (s)				EAL (s)				ELL (s)				$ELL_{Release}$ (s)			
		Norm	SD	P50	SD	Norm	SD	P50	SD	Norm	SD	P50	SD	Norm	SD	P50	SD
M 1	P	0.475	0.138	1.601	0.368	0.656	0.155	3.069	0.534	-0.020	0.103	-0.554	1.184				
	D					0.822	0.151	0.867	0.079	-0.146	0.101	-2.267	0.324	0.136	0.089	-0.280	0.047
M 2	P	0.500	0.104	1.017	0.159	0.732	0.165	1.953	0.194	-0.040	0.097	-0.614	0.282				
	D					0.941	0.119	1.123	0.199	-0.320	0.258	-2.263	0.562	-0.018	0.251	-0.508	0.124
M 3	P	0.700	0.153	1.293	0.235	0.934	0.185	2.309	0.278	-0.062	0.181	-0.764	0.287				
	D					0.870	0.160	0.877	0.126	-0.224	0.114	-2.327	0.351	0.065	0.110	-0.502	0.305
M 4	P	0.418	0.091	0.864	0.114	0.566	0.102	2.350	0.344	-0.057	0.193	-0.851	0.114				
	D					0.703	0.173	1.065	0.086	-0.341	0.190	-2.814	0.513	-0.036	0.174	-0.656	0.185

* For all tables: standard deviations are presented as between-participant SD for normative data and between-trial SD for prosthesis user participant data unless otherwise stated. Red highlighted cells indicate prosthesis user outcomes which were more than two SD from the normative mean.
M = Movement, R = Reach, G = Grasp, T = Transport, RL = Release, P = Pick-up, D = Drop-off.

Table E.5: End Effector Metrics*

		Hand Distance Travelled (mm)					Hand Trajectory Variability (mm)				Number of Movement Units				
		Norm	$SD_{b/n}$	$SD_{w/in}$	P50	SD	Norm	$SD_{b/n}$	P50	SD	Norm	$SD_{b/n}$	$SD_{w/in}$	P50	SD
M 1	R-G	366	52	23	650	82	16	3	47		1	0	0	13	3
	T-RL	646	39	21	713	10	17	4	51		2	0	1	13	2
M 2	R-G	456	56	30	561	129	17	4	52		1	0	0	7	2
	T-RL	700	46	27	763	52	20	5	44		2	0	1	12	3
M 3	R-G	887	35	25	1146	47	26	5	47		2	0	0	6	1
	T-RL	724	46	28	707	16	20	4	35		2	1	1	12	2
M 4	R-G	428	49	24	592	113	14	4	77		1	0	0	11	2
	T-RL	657	46	25	695	32	20	4	54		2	0	1	19	4

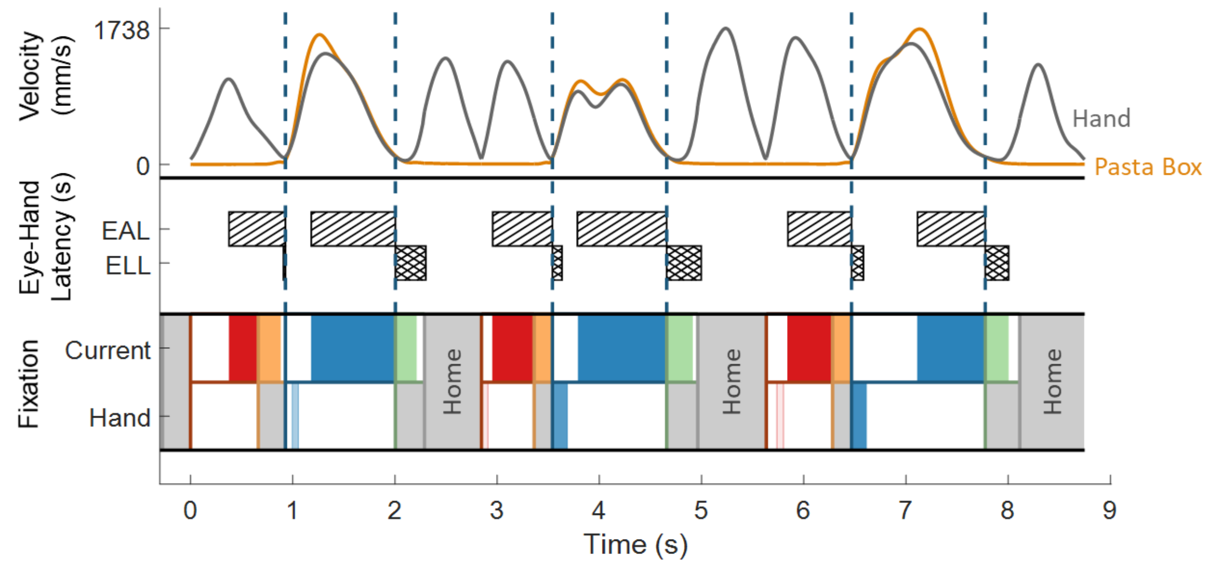
		Peak Hand Velocity (mm/s)					Percent to Peak Hand Velocity (%)				
		Norm	$SD_{b/n}$	$SD_{w/in}$	P50	SD	Norm	$SD_{b/n}$	$SD_{w/in}$	P50	SD
M 1	R-G	866	166	71	910	128	35.2	4.4	4.8	17.3	3.8
	T-RL	1042	88	52	652	46	21.0	2.6	3.0	15.6	4.2
M 2	R-G	1149	139	75	685	154	30.3	7.2	5.9	21.7	5.4
	T-RL	940	70	49	730	48	37.7	9.1	7.0	21.8	5.8
M 3	R-G	1492	187	82	1450	51	36.3	8.4	6.9	26.4	2.2
	T-RL	1009	56	52	736	63	24.7	2.4	2.8	19.3	6.1
M 4	R-G	1157	147	72	799	158	24.5	4.7	5.4	27.8	8.0
	T-RL	979	76	49	594	75	28.0	7.6	8.4	25.2	3.6

		Percent to Peak Hand Deceleration (%)					Percent to Peak Grip Aperture (%)					Peak Grip Aperture (mm)				
		Norm	$SD_{b/n}$	$SD_{w/in}$	P50	SD	Norm	$SD_{b/n}$	$SD_{w/in}$	P50	SD	Norm	$SD_{b/n}$	$SD_{w/in}$	P50	SD
M 1	R-G	62.0	8.7	13.7	28.5	7.5	80.4	4.7	5.1	64.7	41.5	99	4	3	30	17
M 2	R-G	49.8	6.5	6.9	29.3	8.4	73.0	6.3	9.1	75.8	36.8	114	6	4	43	34
M 3	R-G	61.0	5.3	5.9	35.9	6.8	80.4	3.9	4.9	55.6	19.8	114	7	2	49	50
M 4	R-G	62.3	13.5	11.8	33.0	7.4	83.7	5.4	9.2	60.9	24.2	100	5	4	31	4

* For all tables: standard deviations are presented as between-participant SD for normative data and between-trial SD for prosthesis user participant data unless otherwise stated. Red highlighted cells indicate prosthesis user outcomes which were more than two SD from the normative mean.
M = Movement, R = Reach, G = Grasp, T = Transport, RL = Release.

E.2 Pasta Box Task Outcomes

Normative Data Set:



P50:

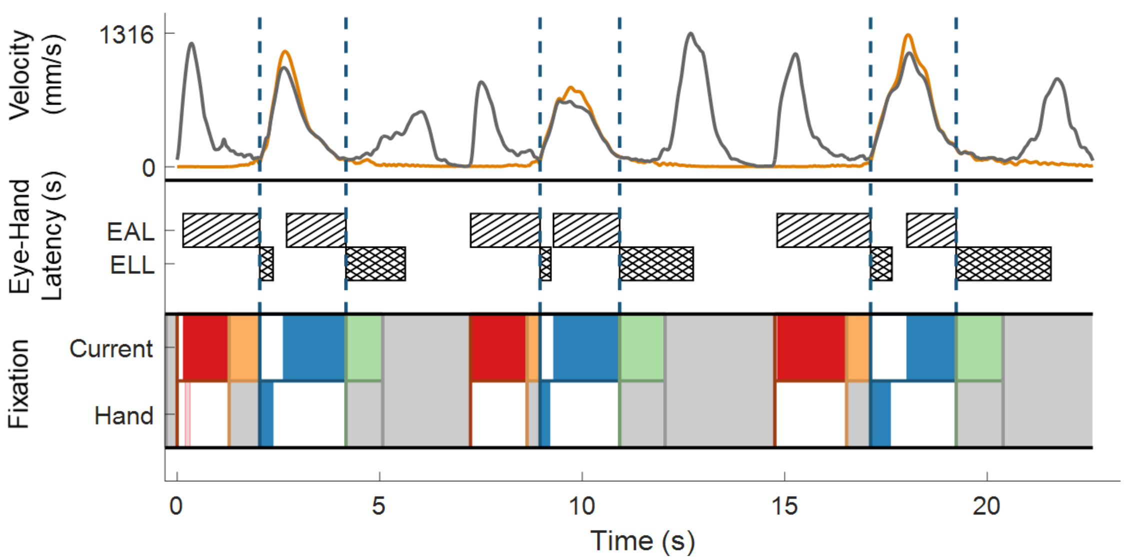


Figure E.3: Summary figures for prosthesis user participant compared with normative data. Top row: velocity plots for hand (grey) and objects (green cup and blue cup). Middle row: Eye Arrival Latencies and Eye Leaving Latencies (at Pick-Up and Drop-Off). Bottom row: fixation plots representing Percent Fixations to 'Current' and 'Hand Only' AOIs throughout each task phase: Reach (red), Grasp (orange), Transport (blue), and Release (green). Opacity level of fixation plots represents probability of fixation. The entire task is plotted with time along the x-axis.

Table E.6: Task performance

Number of successful trials	8
Trial success rate (%)	80%
Errors	1 – Hit frame of shelves
	1 – Movement hesitation
Number of trials analyzed	8

Table E.7: Phase Durations and Relative Phase Durations*

		Duration (s)				Relative Phase Duration (%)			
		Norm	SD	P50	SD	Norm	SD	P50	SD
M 1	R	0.66	0.08	1.28	0.21	29.03	2.01	25.41	3.46
	G	0.27	0.08	0.76	0.32	11.47	2.47	14.58	4.50
	T	1.08	0.12	2.13	0.25	47.13	2.22	42.56	7.29
	RL	0.28	0.07	0.91	0.46	12.37	2.34	17.45	8.02
M 2	R	0.52	0.06	1.39	0.20	24.44	2.01	29.34	4.46
	G	0.18	0.05	0.32	0.08	8.32	1.67	6.77	1.71
	T	1.12	0.13	1.97	0.17	53.00	2.89	41.55	6.22
	RL	0.30	0.08	1.12	0.70	14.24	2.73	22.34	10.15
M 3	R	0.65	0.10	1.77	0.39	26.18	1.82	31.72	7.83
	G	0.19	0.06	0.59	0.44	7.36	1.78	10.42	7.18
	T	1.31	0.16	2.11	0.15	52.91	2.07	37.90	4.97
	RL	0.34	0.07	1.16	0.61	13.56	2.16	19.97	9.50
Total		8.75	1.20	22.61	1.19				

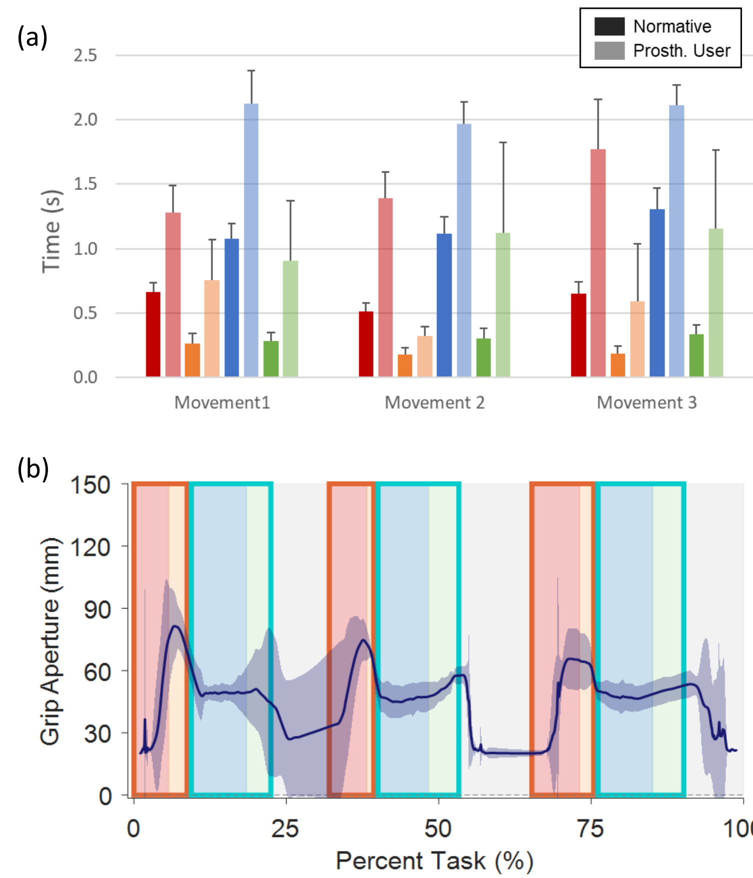


Figure E.4: (a) Phase Durations compared with normative data, (b) Grip Aperture profile. Phases are color coded: Reach (red), Grasp (orange), Transport(blue), and Release (green).

* For all tables: standard deviations are presented as between-participant SD for normative data and between-trial SD for prosthesis user participant data unless otherwise stated. Red highlighted cells indicate prosthesis user outcomes which were more than two SD from the normative mean.
M = Movement, R = Reach, G = Grasp, T = Transport, RL = Release.

Table E.8: Eye Gaze Fixation and Eye-Hand Latency Metrics*

		Mean Percent Fixations (When Fixated) (%)								Mean Number of Fixations							
		Current AOI				Hand Only AOI				Current AOI				Hand Only AOI			
		Norm	SD	P50	SD	Norm	SD	P50	SD	Norm	SD	P50	SD	Norm	SD	P50	SD
M 1	R	42.8	8.6	88.4	7.3	0.0	0.0	7.5	0.0	1.01	0.14	1.00	0.00	0.00	0.00	0.13	0.35
	G	82.7	15.0	100.0	0.0					0.97	0.07	1.00	0.00				
	T	75.1	9.7	71.2	3.9	5.8	2.4	15.8	3.3	1.03	0.05	1.13	0.35	0.32	0.33	1.13	0.35
	RL	71.8	18.0	98.5	4.1					0.99	0.03	1.00	0.00				
M 2	R	77.5	15.0	99.7	0.9	10.5	9.0	0.0	0.0	1.00	0.02	1.00	0.00	0.03	0.10	0.00	0.00
	G	89.4	15.3	100.0	0.0					0.93	0.15	1.00	0.00				
	T	76.9	9.3	83.4	6.1	12.7	6.7	12.3	4.7	1.02	0.06	1.00	0.00	0.75	0.28	1.00	0.00
	RL	81.8	15.1	100.0	0.0					0.99	0.03	1.00	0.00				
M 3	R	66.4	15.8	96.3	4.1	10.5	7.7	0.0	0.0	1.02	0.04	1.00	0.00	0.07	0.19	0.00	0.00
	G	93.6	14.0	100.0	0.0					0.98	0.05	1.00	0.00				
	T	50.0	4.7	57.4	4.6	11.2	3.6	23.3	6.7	1.06	0.09	1.00	0.00	0.85	0.27	1.13	0.35
	RL	64.2	15.8	100.0	0.0					1.00	0.09	1.00	0.00				

		EAL_{Grasp} (s)				EAL (s)				ELL (s)				$ELL_{Release}$ (s)			
		Norm	SD	P50	SD	Norm	SD	P50	SD	Norm	SD	P50	SD	Norm	SD	P50	SD
M 1	P	0.286	0.068	1.134	0.202	0.552	0.114	1.891	0.392	0.019	0.078	-0.328	0.087				
	D					0.823	0.200	1.464	0.335	-0.297	0.201	-1.463	0.425	-0.013	0.188	-0.555	0.455
M 2	P	0.405	0.106	1.390	0.202	0.584	0.141	1.713	0.217	-0.094	0.129	-0.264	0.116				
	D					0.873	0.171	1.634	0.134	-0.338	0.188	-1.816	0.667	-0.034	0.168	-0.695	0.101
M 3	P	0.437	0.134	1.713	0.418	0.623	0.174	2.305	0.481	-0.116	0.091	-0.527	0.185				
	D					0.662	0.100	1.217	0.159	-0.229	0.095	-2.337	0.577	0.109	0.065	-1.180	0.708

* For all tables: standard deviations are presented as between-participant SD for normative data and between-trial SD for prosthesis user participant data unless otherwise stated. Red highlighted cells indicate prosthesis user outcomes which were more than two SD from the normative mean.
M = Movement, R = Reach, G = Grasp, T = Transport, RL = Release, P = Pick-up, D = Drop-off.

Table E.9: End Effector Metrics*

		Hand Distance Travelled (mm)					Hand Trajectory Variability (mm)				Number of Movement Units				
		Norm	SDb/n	SDw/in	P50	SD	Norm	SDb/n	P50	SD	Norm	SDb/n	SDw/in	P50	SD
M 1	R-G	492	26	23	774	33	19	5	51		1	0	0	7	3
	T-RL	935	27	16	1032	80	22	4	75		1	0	0	8	2
M 2	R-G	505	23	19	567	35	15	5	31		1	0	0	6	2
	T-RL	802	61	24	898	48	20	4	59		2	0	0	10	3
M 3	R-G	746	24	14	849	41	19	4	51		1	0	0	9	4
	T-RL	1186	31	18	1403	37	35	8	134		2	0	1	9	3

		Peak Hand Velocity (mm/s)					Percent to Peak Hand Velocity (%)				
		Norm	SDb/n	SDw/in	P50	SD	Norm	SDb/n	SDw/in	P50	SD
M 1	R-G	1164	163	90	1299	148	41.2	4.5	3.0	18.8	3.6
	T-RL	1447	136	81	1074	90	29.3	3.1	3.0	19.1	4.3
M 2	R-G	1352	191	64	924	76	36.8	4.4	3.5	17.9	5.7
	T-RL	1069	112	55	714	54	44.8	8.6	10.5	24.9	9.2
M 3	R-G	1666	261	92	1206	165	35.5	4.0	3.6	21.7	5.5
	T-RL	1598	180	106	1255	74	36.2	3.8	3.8	35.9	8.9

		Percent to Peak Hand Deceleration (%)					Percent to Peak Grip Aperture (%)					Peak Grip Aperture (mm)				
		Norm	SDb/n	SDw/in	P50	SD	Norm	SDb/n	SDw/in	P50	SD	Norm	SDb/n	SDw/in	P50	SD
M 1	R-G	55.7	8.0	7.8	33.7	12.6	73.3	6.5	6.9	62.3	27.1	116	8	8	72	29
M 2	R-G	72.6	8.6	5.6	38.0	23.1	80.1	8.0	4.6	58.0	30.0	106	10	5	85	23
M 3	R-G	72.8	8.4	5.9	39.0	22.4	81.5	4.9	5.0	53.0	24.4	109	8	5	128	164

* For all tables: standard deviations are presented as between-participant SD for normative data and between-trial SD for prosthesis user participant data unless otherwise stated. Red highlighted cells indicate prosthesis user outcomes which were more than two SD from the normative mean.
M = Movement, R = Reach, G = Grasp, T = Transport, RL = Release.

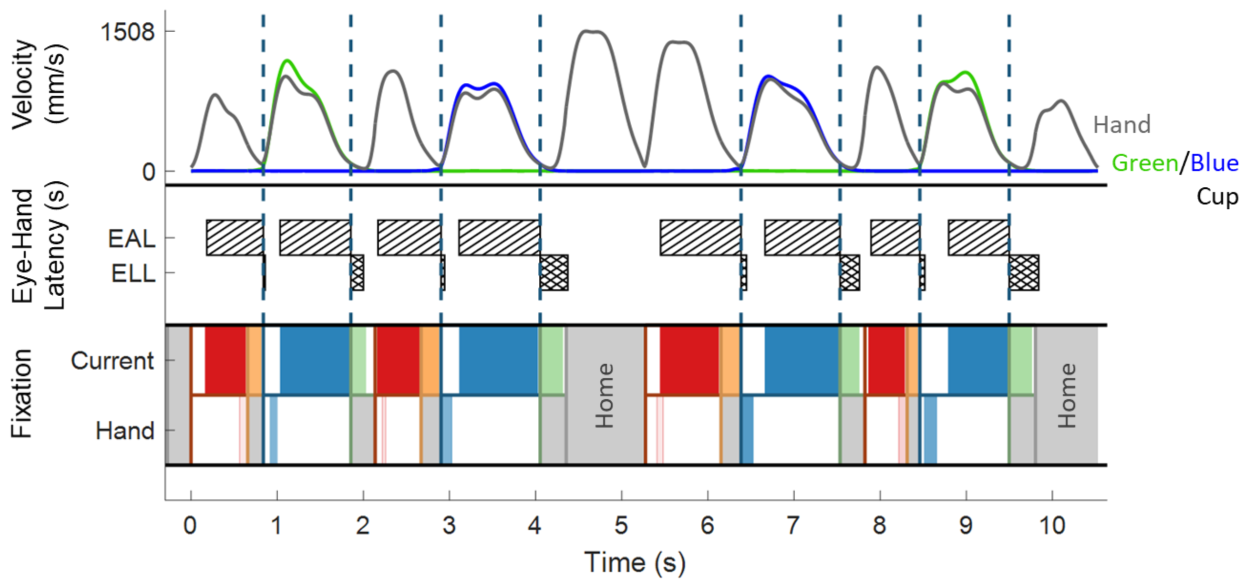
Appendix F. Detailed Report for Participant P94

Table F.1: Participant Information

Age (years)	31
Gender	Male
Level of amputation	Transradial
Amputation side	Right
Length of residual limb (cm)	13
Years since amputation at date of testing	5
Type of prosthesis	Body powered
Type of end-effector	Split hook, voluntary open
Hours per day of use	Not recorded
AM-ULA	16.7
UEFS	76.7

F.1 Cup Transfer Task Outcomes

Normative Data Set:



P94:

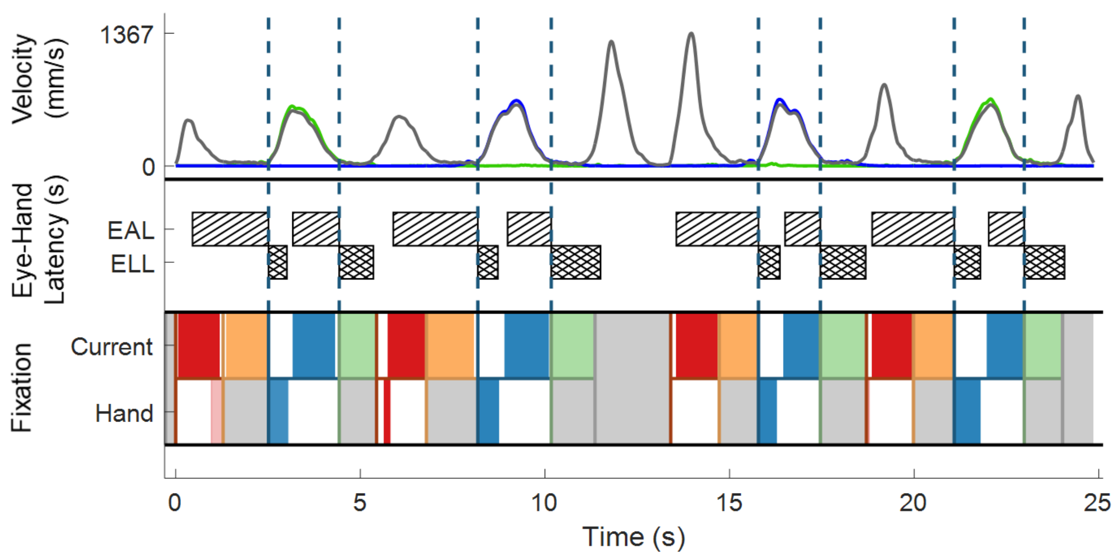


Figure F.1: Summary figures for prosthesis user participant compared with normative data. Top row: velocity plots for hand (grey) and objects (green cup and blue cup). Middle row: Eye Arrival Latencies and Eye Leaving Latencies (at Pick-Up and Drop-Off). Bottom row: fixation plots representing Percent Fixations to 'Current' and 'Hand Only' AOIs throughout each task phase: Reach (red), Grasp (orange), Transport (blue), and Release (green). Opacity level of fixation plots represents probability of fixation. The entire task is plotted with time along the x-axis.

Table F.2: Task performance

Number of successful trials	10
Trial success rate (%)	100%
Errors	N/A
Number of trials analyzed	9 (1 could not be synchronized)

Table F.3: Phase Durations and Relative Phase Durations*

		Duration (s)				Relative Phase Duration (%)			
		Norm	SD	P94	SD	Norm	SD	P94	SD
M 1	R	0.66	0.09	1.29	0.21	30.79	1.72	23.74	3.98
	G	0.18	0.05	1.23	0.41	8.38	1.83	22.25	5.55
	T	1.02	0.10	1.91	0.29	47.77	2.42	35.18	4.05
	RL	0.28	0.07	1.01	0.25	13.06	2.34	18.83	5.12
M 2	R	0.53	0.09	1.35	0.11	24.00	1.67	22.95	2.34
	G	0.23	0.07	1.39	0.41	10.26	1.92	23.43	5.78
	T	1.15	0.12	1.99	0.26	52.15	2.72	33.75	4.34
	RL	0.30	0.07	1.19	0.29	13.59	2.88	19.87	3.58
M 3	R	0.88	0.12	1.31	0.09	34.43	2.03	24.90	2.55
	G	0.23	0.06	1.06	0.27	9.06	1.57	20.00	4.42
	T	1.15	0.12	1.68	0.39	45.30	2.42	31.41	5.25
	RL	0.29	0.09	1.25	0.19	11.21	3.00	23.69	4.14
M 4	R	0.49	0.06	1.27	0.14	24.91	2.60	24.13	3.42
	G	0.15	0.05	1.11	0.29	7.29	1.71	20.65	4.57
	T	1.04	0.12	1.89	0.36	52.57	2.65	35.76	6.18
	RL	0.31	0.09	1.04	0.36	15.23	3.74	19.46	5.94
Total		10.53	1.32	24.86	1.14				

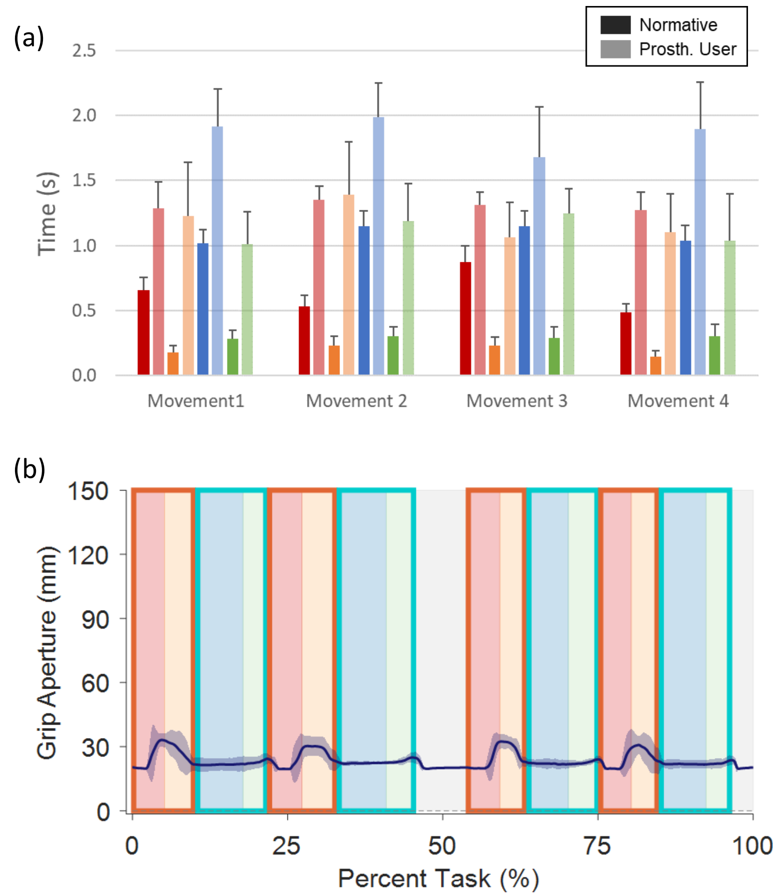


Figure F.2: (a) Phase Durations compared with normative data, (b) Grip Aperture profile. Phases are color coded: Reach (red), Grasp (orange), Transport(blue), and Release (green).

* For all tables: standard deviations are presented as between-participant SD for normative data and between-trial SD for prosthesis user participant data unless otherwise stated. Red highlighted cells indicate prosthesis user outcomes which were more than two SD from the normative mean.
M = Movement, R = Reach, G = Grasp, T = Transport, RL = Release.

Table F.4: Eye Gaze Fixation and Eye-Hand Latency Metrics*

		Mean Percent Fixations (When Fixated) (%)								Mean Number of Fixations							
		Current AOI				Hand Only AOI				Current AOI				Hand Only AOI			
		Norm	SD	P94	SD	Norm	SD	P94	SD	Norm	SD	P94	SD	Norm	SD	P94	SD
M 1	R	71.8	14.6	87.7	17.3	14.3	6.7	29.7	10.6	1.00	0.11	1.00	0.00	0.02	0.04	0.22	0.44
	G	82.5	21.3	95.5	13.4					0.89	0.16	1.00	0.00				
	T	78.8	11.4	60.4	9.4	8.2	4.8	27.2	9.7	1.02	0.03	1.44	0.53	0.52	0.32	0.89	0.33
	RL	58.0	18.2	99.3	1.8					0.87	0.18	1.00	0.00				
M 2	R	92.6	7.4	76.3	18.4	7.5	4.2	12.9	9.0	1.01	0.02	1.00	0.00	0.08	0.09	1.22	0.44
	G	86.7	13.9	93.2	16.6					0.95	0.10	1.00	0.00				
	T	79.5	11.9	60.8	8.2	10.3	4.0	27.5	11.2	1.01	0.02	1.11	0.33	0.58	0.29	1.33	0.50
	RL	82.2	16.7	98.7	3.8					0.94	0.22	1.00	0.00				
M 3	R	77.6	15.3	84.2	21.4	7.3	4.8	0.0	0.0	1.00	0.07	1.22	0.44	0.07	0.17	0.00	0.00
	G	90.4	14.5	94.5	16.5					0.90	0.24	1.00	0.00				
	T	74.5	10.7	58.2	8.6	11.8	6.1	30.0	5.1	1.03	0.05	1.11	0.33	0.74	0.33	1.56	0.73
	RL	75.7	15.3	94.9	9.7					0.94	0.15	1.11	0.33				
M 4	R	85.3	12.1	86.9	10.0	16.8	12.2	6.0	5.1	0.96	0.09	1.11	0.33	0.11	0.18	0.22	0.44
	G	78.1	21.9	100.0	0.0					0.83	0.27	1.00	0.00				
	T	66.2	14.6	51.9	9.9	13.7	9.6	36.9	9.4	0.96	0.14	1.11	0.33	0.68	0.43	1.56	0.53
	RL	82.5	18.9	98.3	5.2					0.94	0.17	1.00	0.00				

		EAL_{Grasp} (s)				EAL (s)				ELL (s)				$ELL_{Release}$ (s)			
		Norm	SD	P94	SD	Norm	SD	P94	SD	Norm	SD	P94	SD	Norm	SD	P94	SD
M 1	P	0.475	0.138	0.830	0.753	0.656	0.155	2.059	0.555	-0.020	0.103	-0.495	0.240				
	D					0.822	0.151	1.256	0.237	-0.146	0.101	-0.926	0.337	0.136	0.089	0.087	0.192
M 2	P	0.500	0.104	0.897	0.431	0.732	0.165	2.290	0.548	-0.040	0.097	-0.543	0.233				
	D					0.941	0.119	1.181	0.174	-0.320	0.258	-1.333	0.318	-0.018	0.251	-0.147	0.193
M 3	P	0.700	0.153	1.161	0.292	0.934	0.185	2.223	0.331	-0.062	0.181	-0.579	0.315				
	D					0.870	0.160	0.956	0.244	-0.224	0.114	-1.229	0.340	0.065	0.110	0.019	0.227
M 4	P	0.418	0.091	1.119	0.164	0.566	0.102	2.224	0.349	-0.057	0.193	-0.708	0.306				
	D					0.703	0.173	0.960	0.279	-0.341	0.190	-1.093	0.415	-0.036	0.174	-0.055	0.252

* For all tables: standard deviations are presented as between-participant SD for normative data and between-trial SD for prosthesis user participant data unless otherwise stated. Red highlighted cells indicate prosthesis user outcomes which were more than two SD from the normative mean.
M = Movement, R = Reach, G = Grasp, T = Transport, RL = Release, P = Pick-up, D = Drop-off.

Table F.5: End Effector Metrics*

		Hand Distance Travelled (mm)					Hand Trajectory Variability (mm)				Number of Movement Units				
		Norm	SDb/n	SDw/in	P94	SD	Norm	SDb/n	P94	SD	Norm	SDb/n	SDw/in	P94	SD
M 1	R-G	366	52	23	338	25	16	3	26		1	0	0	9	2
	T-RL	646	39	21	655	19	17	4	42		2	0	1	10	2
M 2	R-G	456	56	30	515	14	17	4	40		1	0	0	9	3
	T-RL	700	46	27	727	21	20	5	43		2	0	1	9	2
M 3	R-G	887	35	25	881	27	26	5	39		2	0	0	6	2
	T-RL	724	46	28	683	27	20	4	58		2	1	1	8	2
M 4	R-G	428	49	24	538	14	14	4	36		1	0	0	9	2
	T-RL	657	46	25	655	21	20	4	49		2	0	1	8	2

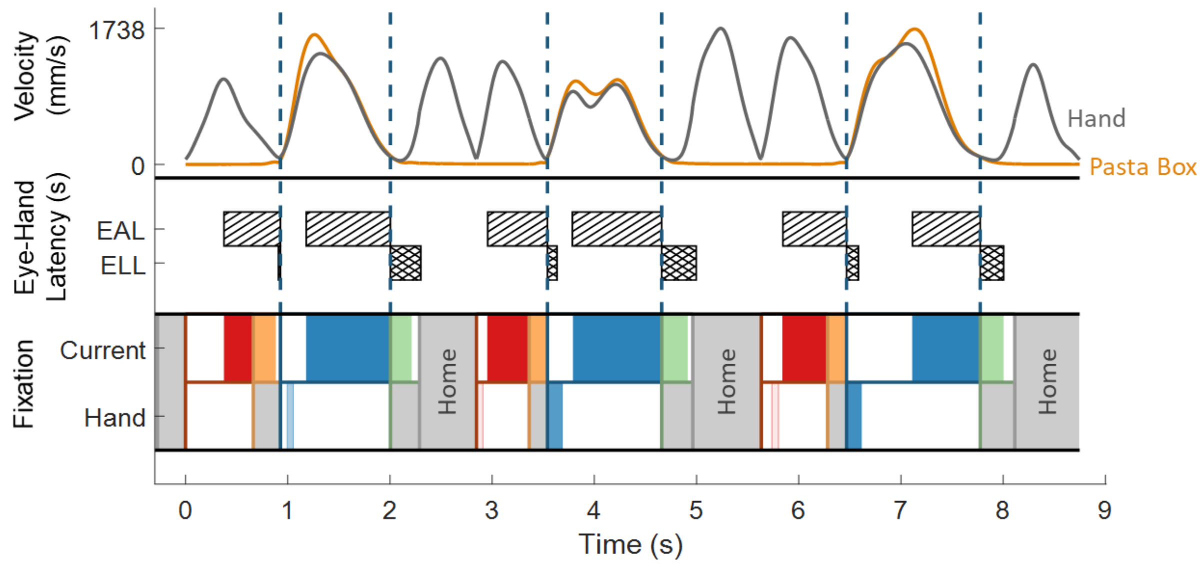
		Peak Hand Velocity (mm/s)					Percent to Peak Hand Velocity (%)				
		Norm	SDb/n	SDw/in	P94	SD	Norm	SDb/n	SDw/in	P94	SD
M 1	R-G	866	166	71	538	63	35.2	4.4	4.8	14.7	3.8
	T-RL	1042	88	52	628	60	21.0	2.6	3.0	25.3	5.5
M 2	R-G	1149	139	75	603	81	30.3	7.2	5.9	23.4	6.8
	T-RL	940	70	49	698	56	37.7	9.1	7.0	34.4	4.4
M 3	R-G	1492	187	82	1408	132	36.3	8.4	6.9	23.6	1.9
	T-RL	1009	56	52	729	76	24.7	2.4	2.8	23.5	7.7
M 4	R-G	1157	147	72	874	59	24.5	4.7	5.4	21.1	3.0
	T-RL	979	76	49	697	55	28.0	7.6	8.4	36.8	5.6

		Percent to Peak Hand Deceleration (%)					Percent to Peak Grip Aperture (%)					Peak Grip Aperture (mm)				
		Norm	SDb/n	SDw/in	P94	SD	Norm	SDb/n	SDw/in	P94	SD	Norm	SDb/n	SDw/in	P94	SD
M 1	R-G	62.0	8.7	13.7	22.4	7.5	80.4	4.7	5.1	56.9	18.6	99	4	3	31	5
M 2	R-G	49.8	6.5	6.9	34.4	8.3	73.0	6.3	9.1	55.6	9.2	114	6	4	31	2
M 3	R-G	61.0	5.3	5.9	30.0	1.7	80.4	3.9	4.9	55.6	10.7	114	7	2	33	2
M 4	R-G	62.3	13.5	11.8	32.2	5.4	83.7	5.4	9.2	62.3	11.2	100	5	4	31	2

* For all tables: standard deviations are presented as between-participant SD for normative data and between-trial SD for prosthesis user participant data unless otherwise stated. Red highlighted cells indicate prosthesis user outcomes which were more than two SD from the normative mean.
M = Movement, R = Reach, G = Grasp, T = Transport, RL = Release.

F.2 Pasta Box Task Outcomes

Normative Data Set:



P94:

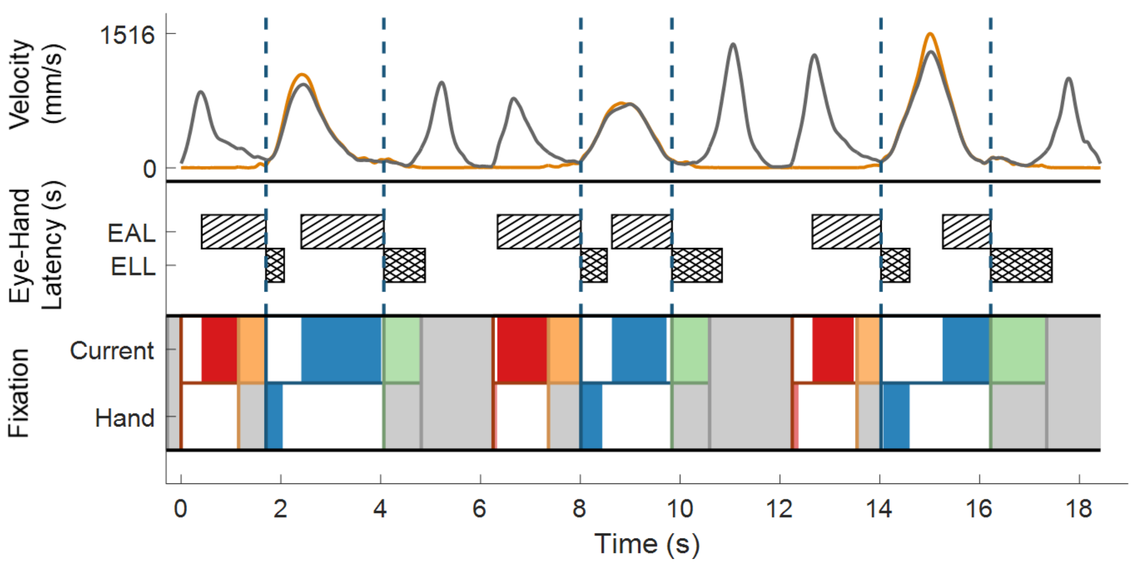


Figure F.3: Summary figures for prosthesis user participant compared with normative data. Top row: velocity plots for hand (grey) and objects (green cup and blue cup). Middle row: Eye Arrival Latencies and Eye Leaving Latencies (at Pick-Up and Drop-Off). Bottom row: fixation plots representing Percent Fixations to 'Current' and 'Hand Only' AOIs throughout each task phase: Reach (red), Grasp (orange), Transport (blue), and Release (green). Opacity level of fixation plots represents probability of fixation. The entire task is plotted with time along the x-axis.

Table F.6: Task performance

Number of successful trials	10
Trial success rate (%)	100%
Errors	N/A
Number of trials analyzed	10

Table F.7: Phase Durations and Relative Phase Durations*

		Duration (s)				Relative Phase Duration (%)			
		Norm	SD	P94	SD	Norm	SD	P94	SD
M 1	R	0.66	0.08	1.15	0.14	29.03	2.01	24.26	3.90
	G	0.27	0.08	0.55	0.22	11.47	2.47	11.37	4.20
	T	1.08	0.12	2.36	0.46	47.13	2.22	48.80	4.53
	RL	0.28	0.07	0.75	0.12	12.37	2.34	15.57	1.43
M 2	R	0.52	0.06	1.11	0.14	24.44	2.01	25.63	2.93
	G	0.18	0.05	0.65	0.26	8.32	1.67	14.75	5.35
	T	1.12	0.13	1.82	0.11	53.00	2.89	42.37	4.88
	RL	0.30	0.08	0.75	0.18	14.24	2.73	17.25	3.07
M 3	R	0.65	0.10	1.30	0.10	26.18	1.82	25.55	2.29
	G	0.19	0.06	0.48	0.14	7.36	1.78	9.43	2.63
	T	1.31	0.16	2.20	0.35	52.91	2.07	43.12	6.37
	RL	0.34	0.07	1.12	0.33	13.56	2.16	21.90	5.69
Total		8.75	1.20	18.42	1.09				

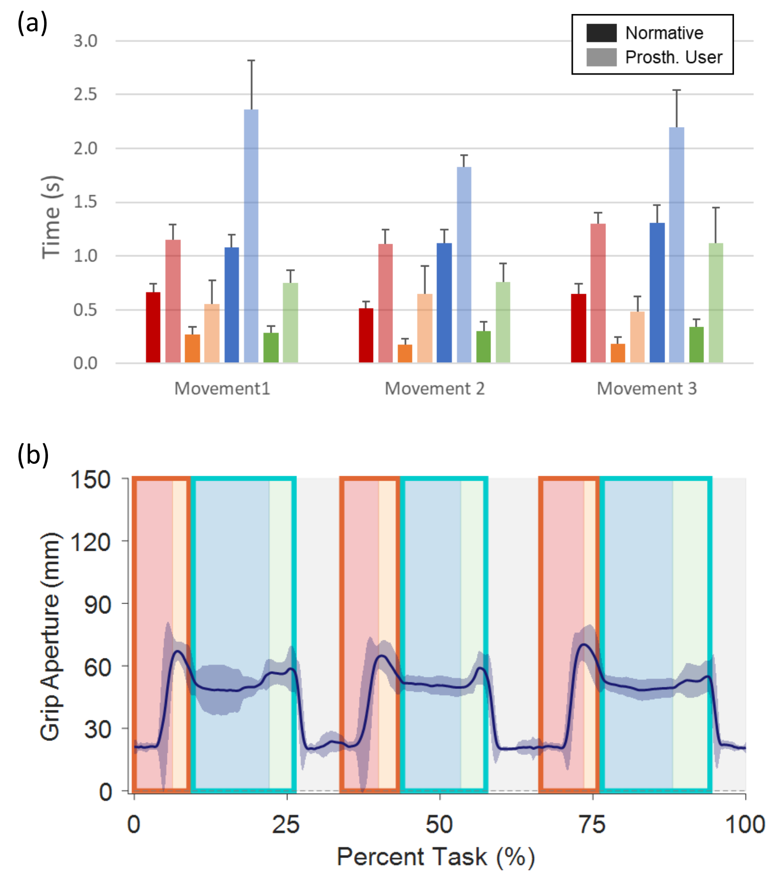


Figure F.4: (a) Phase Durations compared with normative data, (b) Grip Aperture profile. Phases are color coded: Reach (red), Grasp (orange), Transport(blue), and Release (green).

* For all tables: standard deviations are presented as between-participant SD for normative data and between-trial SD for prosthesis user participant data unless otherwise stated. Red highlighted cells indicate prosthesis user outcomes which were more than two SD from the normative mean.
M = Movement, R = Reach, G = Grasp, T = Transport, RL = Release.

Table F.8: Eye Gaze Fixation and Eye-Hand Latency Metrics*

		Mean Percent Fixations (When Fixated) (%)								Mean Number of Fixations							
		Current AOI				Hand Only AOI				Current AOI				Hand Only AOI			
		Norm	SD	P94	SD	Norm	SD	P94	SD	Norm	SD	P94	SD	Norm	SD	P94	SD
M 1	R	42.8	8.6	62.2	16.9	0.0	0.0	2.2	0.0	1.01	0.14	1.10	0.32	0.00	0.00	0.10	0.32
	G	82.7	15.0	100.0	0.0					0.97	0.07	1.00	0.00				
	T	75.1	9.7	66.9	8.7	5.8	2.4	14.0	6.7	1.03	0.05	1.00	0.00	0.32	0.33	1.00	0.00
	RL	71.8	18.0	100.0	0.0					0.99	0.03	0.90	0.32				
M 2	R	77.5	15.0	90.6	8.2	10.5	9.0	6.6	4.0	1.00	0.02	1.20	0.42	0.03	0.10	0.50	0.53
	G	89.4	15.3	98.7	4.3					0.93	0.15	1.10	0.32				
	T	76.9	9.3	59.8	12.8	12.7	6.7	22.1	11.3	1.02	0.06	1.90	0.74	0.75	0.28	1.00	0.00
	RL	81.8	15.1	100.0	0.0					0.99	0.03	1.00	0.00				
M 3	R	66.4	15.8	62.7	15.8	10.5	7.7	9.4	5.7	1.02	0.04	1.10	0.32	0.07	0.19	0.60	0.52
	G	93.6	14.0	91.2	26.3					0.98	0.05	0.90	0.32				
	T	50.0	4.7	42.3	7.7	11.2	3.6	23.9	10.8	1.06	0.09	1.10	0.32	0.85	0.27	1.00	0.00
	RL	64.2	15.8	99.8	0.8					1.00	0.09	1.00	0.00				

		EAL_{Grasp} (s)				EAL (s)				ELL (s)				$ELL_{Release}$ (s)			
		Norm	SD	P94	SD	Norm	SD	P94	SD	Norm	SD	P94	SD	Norm	SD	P94	SD
M 1	P	0.286	0.068	0.739	0.242	0.552	0.114	1.288	0.255	0.019	0.078	-0.363	0.149				
	D					0.823	0.200	1.653	0.428	-0.297	0.201	-0.826	0.505	-0.013	0.188	-0.076	0.490
M 2	P	0.405	0.106	1.018	0.182	0.584	0.141	1.668	0.304	-0.094	0.129	-0.523	0.182				
	D					0.873	0.171	1.202	0.205	-0.338	0.188	-1.002	0.240	-0.034	0.168	-0.248	0.145
M 3	P	0.437	0.134	0.893	0.153	0.623	0.174	1.374	0.211	-0.116	0.091	-0.573	0.192				
	D					0.662	0.100	0.957	0.273	-0.229	0.095	-1.226	0.379	0.109	0.065	-0.104	0.088

* For all tables: standard deviations are presented as between-participant SD for normative data and between-trial SD for prosthesis user participant data unless otherwise stated. Red highlighted cells indicate prosthesis user outcomes which were more than two SD from the normative mean.

M = Movement, R = Reach, G = Grasp, T = Transport, RL = Release, P = Pick-up, D = Drop-off.

Table F.9: End Effector Metrics*

		Hand Distance Travelled (mm)					Hand Trajectory Variability (mm)				Number of Movement Units				
		Norm	$SD_{b/n}$	$SD_{w/in}$	P94	SD	Norm	$SD_{b/n}$	P94	SD	Norm	$SD_{b/n}$	$SD_{w/in}$	P94	SD
M 1	R-G	492	26	23	579	42	19	5	40		1	0	0	5	1
	T-RL	935	27	16	966	46	22	4	89		1	0	0	7	3
M 2	R-G	505	23	19	543	44	15	5	43		1	0	0	4	2
	T-RL	802	61	24	859	21	20	4	38		2	0	0	5	2
M 3	R-G	746	24	14	811	14	19	4	32		1	0	0	3	1
	T-RL	1186	31	18	1324	25	35	8	69		2	0	1	7	1

		Peak Hand Velocity (mm/s)					Percent to Peak Hand Velocity (%)				
		Norm	$SD_{b/n}$	$SD_{w/in}$	P94	SD	Norm	$SD_{b/n}$	$SD_{w/in}$	P94	SD
M 1	R-G	1164	163	90	916	66	41.2	4.5	3.0	23.9	4.3
	T-RL	1447	136	81	1073	127	29.3	3.1	3.0	21.9	5.2
M 2	R-G	1352	191	64	896	106	36.8	4.4	3.5	23.9	5.7
	T-RL	1069	112	55	762	42	44.8	8.6	10.5	35.5	6.0
M 3	R-G	1666	261	92	1303	181	35.5	4.0	3.6	25.9	3.1
	T-RL	1598	180	106	1352	122	36.2	3.8	3.8	29.8	2.8

		Percent to Peak Hand Deceleration (%)					Percent to Peak Grip Aperture (%)					Peak Grip Aperture (mm)				
		Norm	$SD_{b/n}$	$SD_{w/in}$	P94	SD	Norm	$SD_{b/n}$	$SD_{w/in}$	P94	SD	Norm	$SD_{b/n}$	$SD_{w/in}$	P94	SD
M 1	R-G	55.7	8.0	7.8	34.1	5.1	73.3	6.5	6.9	75.1	7.9	116	8	8	68	2
M 2	R-G	72.6	8.6	5.6	33.2	11.2	80.1	8.0	4.6	64.3	9.8	106	10	5	66	4
M 3	R-G	72.8	8.4	5.9	35.0	5.5	81.5	4.9	5.0	71.1	7.4	109	8	5	71	4

* For all tables: standard deviations are presented as between-participant SD for normative data and between-trial SD for prosthesis user participant data unless otherwise stated. Red highlighted cells indicate prosthesis user outcomes which were more than two SD from the normative mean.
M = Movement, R = Reach, G = Grasp, T = Transport, RL = Release.

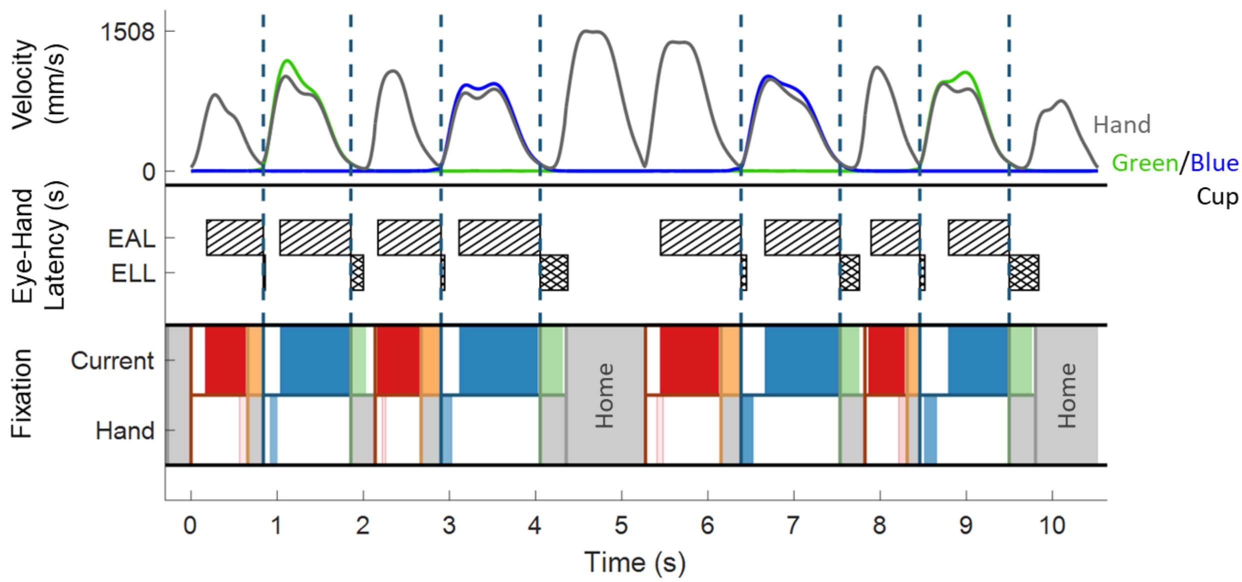
Appendix G. Detailed Report for Participant P44

Table G.1: Participant Information

Age (years)	37
Gender	Male
Level of amputation	Transhumeral
Amputation side	Left
Length of residual limb (cm)	Not measured
Years since amputation at date of testing	8
Type of prosthesis	Body powered
Type of end-effector	Split hook, voluntary open
Hours per day of use	14
AM-ULA	16.7
UEFS	76.4

G.1 Cup Transfer Task Outcomes

Normative Data Set:



P44:

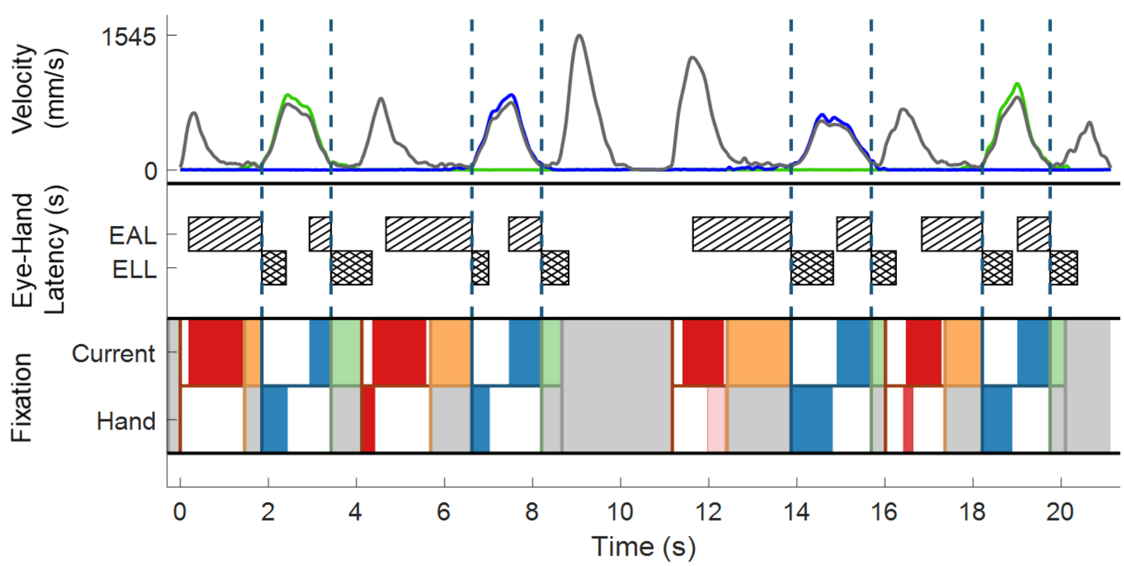


Figure G.1: Summary figures for prosthesis user participant compared with normative data. Top row: velocity plots for hand (grey) and objects (green cup and blue cup). Middle row: Eye Arrival Latencies and Eye Leaving Latencies (at Pick-Up and Drop-Off). Bottom row: fixation plots representing Percent Fixations to 'Current' and 'Hand Only' AOIs throughout each task phase: Reach (red), Grasp (orange), Transport (blue), and Release (green). Opacity level of fixation plots represents probability of fixation. The entire task is plotted with time along the x-axis.

Table G.2: Task performance

Number of successful trials	5
Trial success rate (%)	83%
Errors	1 – Dropped cup
Number of trials analyzed	5

Table G.3: Phase Durations and Relative Phase Durations*

		Duration (s)				Relative Phase Duration (%)			
		Norm	SD	P44	SD	Norm	SD	P44	SD
M 1	R	0.66	0.09	1.46	0.30	30.79	1.72	35.33	5.31
	G	0.18	0.05	0.39	0.06	8.38	1.83	9.57	1.67
	T	1.02	0.10	1.57	0.20	47.77	2.42	38.30	4.98
	RL	0.28	0.07	0.70	0.17	13.06	2.34	16.80	3.15
M 2	R	0.53	0.09	1.56	0.24	24.00	1.67	34.24	3.67
	G	0.23	0.07	0.94	0.17	10.26	1.92	20.76	4.45
	T	1.15	0.12	1.58	0.14	52.15	2.72	34.79	1.93
	RL	0.30	0.07	0.46	0.15	13.59	2.88	10.21	3.48
M 3	R	0.88	0.12	1.25	0.15	34.43	2.03	26.37	6.19
	G	0.23	0.06	1.45	0.86	9.06	1.57	28.73	12.77
	T	1.15	0.12	1.82	0.33	45.30	2.42	38.13	7.85
	RL	0.29	0.09	0.32	0.16	11.21	3.00	6.77	3.95
M 4	R	0.49	0.06	1.35	0.18	24.91	2.60	33.22	4.40
	G	0.15	0.05	0.85	0.45	7.29	1.71	20.21	8.93
	T	1.04	0.12	1.54	0.18	52.57	2.65	37.92	5.34
	RL	0.31	0.09	0.35	0.10	15.23	3.74	8.66	2.83
Total		10.53	1.32	21.13	1.14				

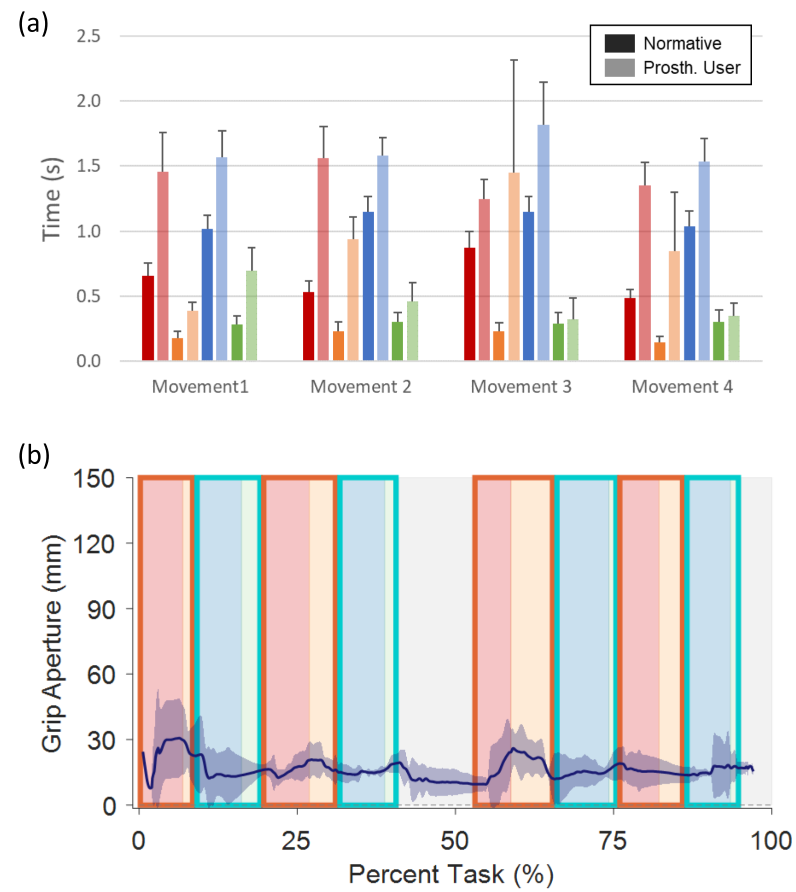


Figure G.2: (a) Phase Durations compared with normative data, (b) Grip Aperture profile. Phases are color coded: Reach (red), Grasp (orange), Transport(blue), and Release (green).

* For all tables: standard deviations are presented as between-participant SD for normative data and between-trial SD for prosthesis user participant data unless otherwise stated. Red highlighted cells indicate prosthesis user outcomes which were more than two SD from the normative mean.
M = Movement, R = Reach, G = Grasp, T = Transport, RL = Release.

Table G.4: Eye Gaze Fixation and Eye-Hand Latency Metrics*

		Mean Percent Fixations (When Fixated) (%)								Mean Number of Fixations							
		Current AOI				Hand Only AOI				Current AOI				Hand Only AOI			
		Norm	SD	P44	SD	Norm	SD	P44	SD	Norm	SD	P44	SD	Norm	SD	P44	SD
M 1	R	71.8	14.6	86.3	4.9	14.3	6.7	0.0	0.0	1.00	0.11	1.00	0.00	0.02	0.04	0.00	0.00
	G	82.5	21.3	100.0	0.0					0.89	0.16	1.00	0.00				
	T	78.8	11.4	31.4	5.5	8.2	4.8	35.9	17.5	1.02	0.03	1.00	0.00	0.52	0.32	1.40	0.89
	RL	58.0	18.2	100.0	0.0					0.87	0.18	1.00	0.00				
M 2	R	92.6	7.4	79.3	13.5	7.5	4.2	18.7	11.6	1.01	0.02	1.00	0.00	0.08	0.09	1.20	0.45
	G	86.7	13.9	100.0	0.0					0.95	0.10	1.00	0.00				
	T	79.5	11.9	47.1	6.7	10.3	4.0	25.3	16.4	1.01	0.02	1.00	0.00	0.58	0.29	1.20	0.45
	RL	82.2	16.7	100.0	0.0					0.94	0.22	1.00	0.00				
M 3	R	77.6	15.3	74.8	10.1	7.3	4.8	32.9	0.0	1.00	0.07	1.00	0.00	0.07	0.17	0.20	0.45
	G	90.4	14.5	100.0	0.0					0.90	0.24	1.00	0.00				
	T	74.5	10.7	44.7	16.9	11.8	6.1	49.2	18.1	1.03	0.05	1.00	0.00	0.74	0.33	1.20	0.45
	RL	75.7	15.3	100.0	0.0					0.94	0.15	1.00	0.00				
M 4	R	85.3	12.1	58.9	4.9	16.8	12.2	16.9	9.9	0.96	0.09	1.20	0.45	0.11	0.18	0.80	0.84
	G	78.1	21.9	100.0	0.0					0.83	0.27	1.00	0.00				
	T	66.2	14.6	48.1	3.1	13.7	9.6	43.4	8.6	0.96	0.14	1.00	0.00	0.68	0.43	1.20	0.45
	RL	82.5	18.9	100.0	0.0					0.94	0.17	1.00	0.00				

		EAL_{Grasp} (s)				EAL (s)				ELL (s)				$ELL_{Release}$ (s)			
		Norm	SD	P44	SD	Norm	SD	P44	SD	Norm	SD	P44	SD	Norm	SD	P44	SD
M 1	P	0.475	0.138	1.267	0.320	0.656	0.155	1.658	0.346	-0.020	0.103	-0.548	0.344				
	D					0.822	0.151	0.490	0.084	-0.146	0.101	-0.927	0.338	0.136	0.089	-0.228	0.240
M 2	P	0.500	0.104	1.012	0.575	0.732	0.165	1.950	0.642	-0.040	0.097	-0.378	0.257				
	D					0.941	0.119	0.740	0.081	-0.320	0.258	-0.613	0.229	-0.018	0.251	-0.152	0.097
M 3	P	0.700	0.153	0.778	0.450	0.934	0.185	2.230	0.954	-0.062	0.181	-0.955	0.502				
	D					0.870	0.160	0.778	0.192	-0.224	0.114	-0.560	0.221	0.065	0.110	-0.238	0.110
M 4	P	0.418	0.091	0.527	0.444	0.566	0.102	1.375	0.792	-0.057	0.193	-0.675	0.182				
	D					0.703	0.173	0.737	0.054	-0.341	0.190	-0.617	0.128	-0.036	0.174	-0.269	0.051

* For all tables: standard deviations are presented as between-participant SD for normative data and between-trial SD for prosthesis user participant data unless otherwise stated. Red highlighted cells indicate prosthesis user outcomes which were more than two SD from the normative mean.
M = Movement, R = Reach, G = Grasp, T = Transport, RL = Release, P = Pick-up, D = Drop-off.

Table G.5: End Effector Metrics*

		Hand Distance Travelled (mm)					Hand Trajectory Variability (mm)				Number of Movement Units				
		Norm	SDb/n	SDw/in	P44	SD	Norm	SDb/n	P44	SD	Norm	SDb/n	SDw/in	P44	SD
M 1	R-G	366	52	23	373	38	16	3	26		1	0	0	6	1
	T-RL	646	39	21	748	36	17	4	40		2	0	1	6	3
M 2	R-G	456	56	30	574	16	17	4	35		1	0	0	8	1
	T-RL	700	46	27	701	7	20	5	34		2	0	1	4	1
M 3	R-G	887	35	25	1055	72	26	5	105		2	0	0	8	4
	T-RL	724	46	28	653	15	20	4	53		2	1	1	4	2
M 4	R-G	428	49	24	556	59	14	4	50		1	0	0	7	3
	T-RL	657	46	25	680	18	20	4	27		2	0	1	4	1

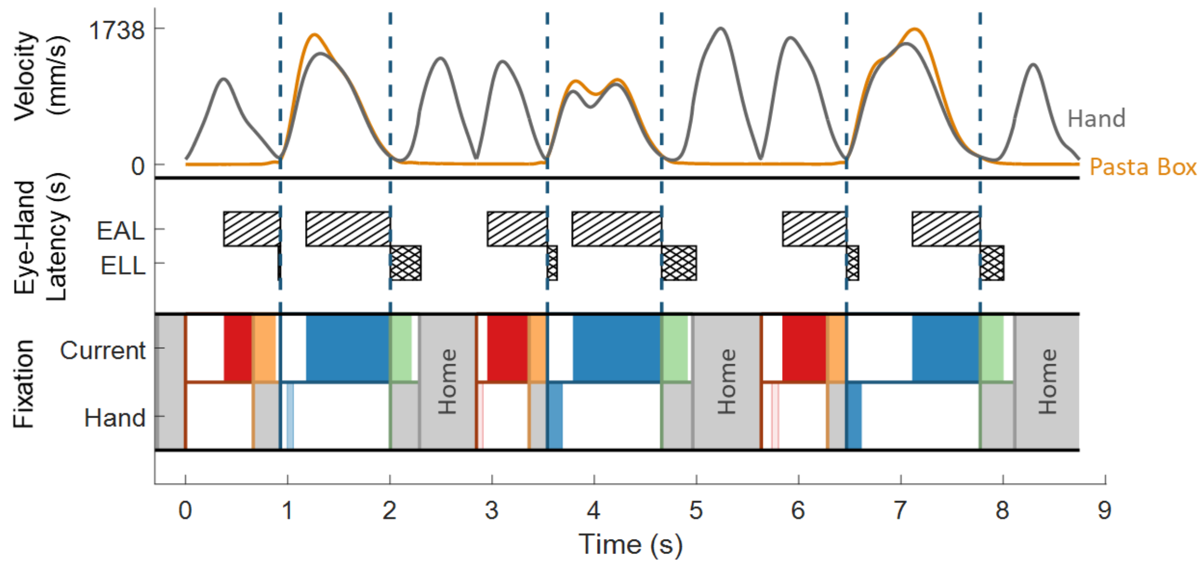
		Peak Hand Velocity (mm/s)					Percent to Peak Hand Velocity (%)				
		Norm	SDb/n	SDw/in	P44	SD	Norm	SDb/n	SDw/in	P44	SD
M 1	R-G	866	166	71	713	76	35.2	4.4	4.8	16.7	3.3
	T-RL	1042	88	52	793	100	21.0	2.6	3.0	27.7	5.6
M 2	R-G	1149	139	75	957	169	30.3	7.2	5.9	18.8	4.1
	T-RL	940	70	49	794	82	37.7	9.1	7.0	44.1	6.7
M 3	R-G	1492	187	82	1505	108	36.3	8.4	6.9	20.4	6.0
	T-RL	1009	56	52	702	100	24.7	2.4	2.8	40.8	10.4
M 4	R-G	1157	147	72	833	159	24.5	4.7	5.4	22.2	7.2
	T-RL	979	76	49	852	66	28.0	7.6	8.4	43.7	2.8

		Percent to Peak Hand Deceleration (%)					Percent to Peak Grip Aperture (%)					Peak Grip Aperture (mm)				
		Norm	SDb/n	SDw/in	P44	SD	Norm	SDb/n	SDw/in	P44	SD	Norm	SDb/n	SDw/in	P44	SD
M 1	R-G	62.0	8.7	13.7	26.5	5.5	80.4	4.7	5.1	86.2	21.4	99	4	3	25	10
M 2	R-G	49.8	6.5	6.9	22.9	4.1	73.0	6.3	9.1	84.2	15.3	114	6	4	21	6
M 3	R-G	61.0	5.3	5.9	29.6	8.0	80.4	3.9	4.9	67.1	20.2	114	7	2	23	12
M 4	R-G	62.3	13.5	11.8	33.2	9.2	83.7	5.4	9.2	95.6	10.8	100	5	4	14	2

* For all tables: standard deviations are presented as between-participant SD for normative data and between-trial SD for prosthesis user participant data unless otherwise stated. Red highlighted cells indicate prosthesis user outcomes which were more than two SD from the normative mean.
M = Movement, R = Reach, G = Grasp, T = Transport, RL = Release.

G.2 Pasta Box Task Outcomes

Normative Data Set:



P44:

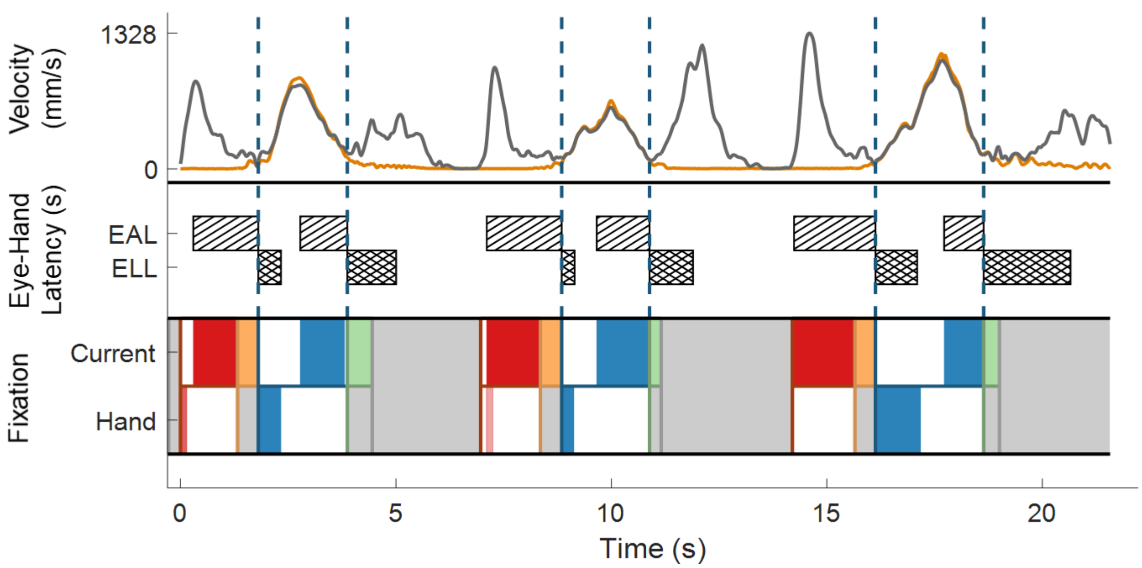


Figure G.3: Summary figures for prosthesis user participant compared with normative data. Top row: velocity plots for hand (grey) and objects (green cup and blue cup). Middle row: Eye Arrival Latencies and Eye Leaving Latencies (at Pick-Up and Drop-Off). Bottom row: fixation plots representing Percent Fixations to 'Current' and 'Hand Only' AOIs throughout each task phase: Reach (red), Grasp (orange), Transport (blue), and Release (green). Opacity level of fixation plots represents probability of fixation. The entire task is plotted with time along the x-axis.

Table G.6: Task performance

Number of successful trials	5
Trial success rate (%)	56%
Errors	4 – Dropped box
Number of trials analyzed	3

Table G.7: Phase Durations and Relative Phase Durations*

		Duration (s)				Relative Phase Duration (%)			
		Norm	SD	P44	SD	Norm	SD	P44	SD
M 1	R	0.66	0.08	1.33	0.17	29.03	2.01	29.84	3.86
	G	0.27	0.08	0.48	0.10	11.47	2.47	10.94	2.99
	T	1.08	0.12	2.07	0.24	47.13	2.22	46.90	8.73
	RL	0.28	0.07	0.58	0.60	12.37	2.34	12.32	11.85
M 2	R	0.52	0.06	1.39	0.24	24.44	2.01	32.98	4.63
	G	0.18	0.05	0.49	0.13	8.32	1.67	11.79	2.90
	T	1.12	0.13	2.04	0.10	53.00	2.89	48.82	4.58
	RL	0.30	0.08	0.27	0.08	14.24	2.73	6.41	1.61
M 3	R	0.65	0.10	1.45	0.19	26.18	1.82	30.28	3.61
	G	0.19	0.06	0.48	0.17	7.36	1.78	10.16	4.30
	T	1.31	0.16	2.51	0.35	52.91	2.07	52.12	2.52
	RL	0.34	0.07	0.37	0.22	13.56	2.16	7.44	3.95
Total		8.75	1.20	21.58	0.77				

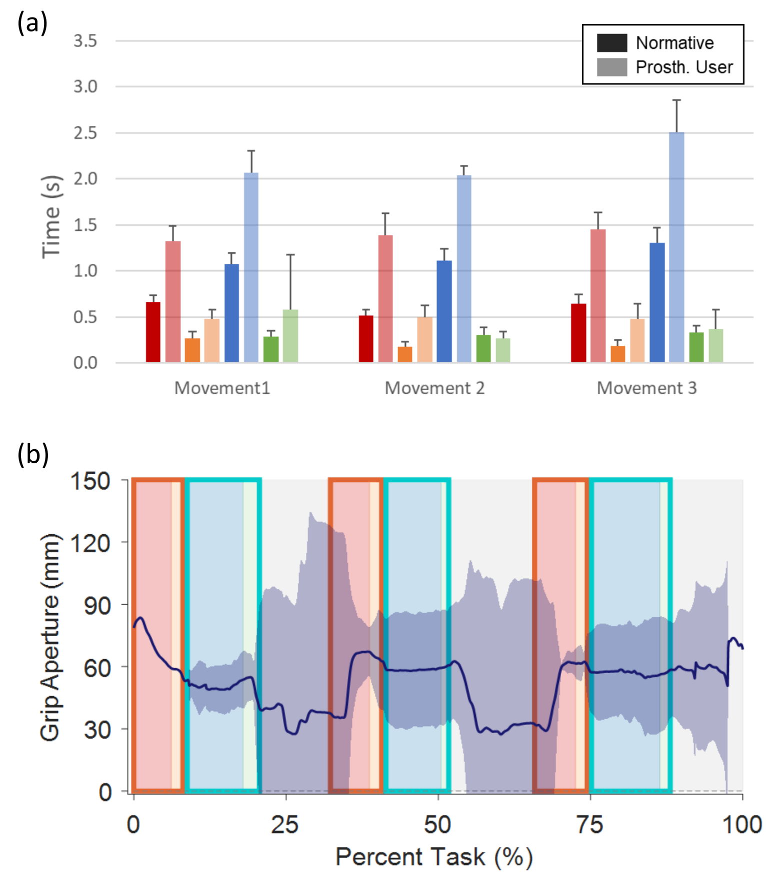


Figure G.4: (a) Phase Durations compared with normative data, (b) Grip Aperture profile. Phases are color coded: Reach (red), Grasp (orange), Transport(blue), and Release (green).

* For all tables: standard deviations are presented as between-participant SD for normative data and between-trial SD for prosthesis user participant data unless otherwise stated. Red highlighted cells indicate prosthesis user outcomes which were more than two SD from the normative mean.
M = Movement, R = Reach, G = Grasp, T = Transport, RL = Release.

Table G.8: Eye Gaze Fixation and Eye-Hand Latency Metrics*

		Mean Percent Fixations (When Fixated) (%)								Mean Number of Fixations							
		Current AOI				Hand Only AOI				Current AOI				Hand Only AOI			
		Norm	SD	P44	SD	Norm	SD	P44	SD	Norm	SD	P44	SD	Norm	SD	P44	SD
M 1	R	42.8	8.6	77.8	4.2	0.0	0.0	10.3	7.3	1.01	0.14	1.00	0.00	0.00	0.00	0.67	0.58
	G	82.7	15.0	100.0	0.0					0.97	0.07	1.00	0.00				
	T	75.1	9.7	49.3	1.8	5.8	2.4	25.9	5.0	1.03	0.05	1.33	0.58	0.32	0.33	1.00	0.00
	RL	71.8	18.0	98.9	1.9					0.99	0.03	1.00	0.00				
M 2	R	77.5	15.0	89.6	10.0	10.5	9.0	10.0	0.0	1.00	0.02	1.00	0.00	0.03	0.10	0.33	0.58
	G	89.4	15.3	100.0	0.0					0.93	0.15	1.00	0.00				
	T	76.9	9.3	60.2	2.4	12.7	6.7	13.6	4.6	1.02	0.06	1.00	0.00	0.75	0.28	1.00	0.00
	RL	81.8	15.1	100.0	0.0					0.99	0.03	1.00	0.00				
M 3	R	66.4	15.8	97.6	4.2	10.5	7.7	0.0	0.0	1.02	0.04	1.00	0.00	0.07	0.19	0.00	0.00
	G	93.6	14.0	100.0	0.0					0.98	0.05	1.00	0.00				
	T	50.0	4.7	36.9	4.7	11.2	3.6	40.1	17.5	1.06	0.09	1.00	0.00	0.85	0.27	1.67	1.15
	RL	64.2	15.8	100.0	0.0					1.00	0.09	1.00	0.00				

		EAL_{Grasp} (s)				EAL (s)				ELL (s)				$ELL_{Release}$ (s)			
		Norm	SD	P44	SD	Norm	SD	P44	SD	Norm	SD	P44	SD	Norm	SD	P44	SD
M 1	P	0.286	0.068	1.028	0.099	0.552	0.114	1.508	0.008	0.019	0.078	-0.528	0.063				
	D					0.823	0.200	1.092	0.271	-0.297	0.201	-1.133	0.423	-0.013	0.188	-0.556	0.640
M 2	P	0.405	0.106	1.244	0.286	0.584	0.141	1.739	0.219	-0.094	0.129	-0.300	0.096				
	D					0.873	0.171	1.225	0.036	-0.338	0.188	-1.008	0.175	-0.034	0.168	-0.739	0.134
M 3	P	0.437	0.134	1.414	0.152	0.623	0.174	1.889	0.211	-0.116	0.091	-0.969	0.677				
	D					0.662	0.100	0.917	0.075	-0.229	0.095	-2.017	0.634	0.109	0.065	-1.650	0.780

* For all tables: standard deviations are presented as between-participant SD for normative data and between-trial SD for prosthesis user participant data unless otherwise stated. Red highlighted cells indicate prosthesis user outcomes which were more than two SD from the normative mean.
M = Movement, R = Reach, G = Grasp, T = Transport, RL = Release, P = Pick-up, D = Drop-off.

Table G.9: End Effector Metrics*

		Hand Distance Travelled (mm)					Hand Trajectory Variability (mm)				Number of Movement Units				
		Norm	$SD_{b/n}$	$SD_{w/in}$	P44	SD	Norm	$SD_{b/n}$	P44	SD	Norm	$SD_{b/n}$	$SD_{w/in}$	P44	SD
M 1	R-G	492	26	23	611	29	19	5	16		1	0	0	6	1
	T-RL	935	27	16	1102	210	22	4	109		1	0	0	5	2
M 2	R-G	505	23	19	555	51	15	5	31		1	0	0	6	2
	T-RL	802	61	24	746	22	20	4	36		2	0	0	6	2
M 3	R-G	746	24	14	850	75	19	4	35		1	0	0	5	2
	T-RL	1186	31	18	1371	65	35	8	61		2	0	1	6	1

		Peak Hand Velocity (mm/s)					Percent to Peak Hand Velocity (%)				
		Norm	$SD_{b/n}$	$SD_{w/in}$	P44	SD	Norm	$SD_{b/n}$	$SD_{w/in}$	P44	SD
M 1	R-G	1164	163	90	869	133	41.2	4.5	3.0	20.0	1.7
	T-RL	1447	136	81	990	43	29.3	3.1	3.0	59.3	34.0
M 2	R-G	1352	191	64	1014	148	36.8	4.4	3.5	17.6	1.7
	T-RL	1069	112	55	622	42	44.8	8.6	10.5	51.6	5.2
M 3	R-G	1666	261	92	1360	50	35.5	4.0	3.6	19.9	2.7
	T-RL	1598	180	106	1070	67	36.2	3.8	3.8	52.6	2.8

		Percent to Peak Hand Deceleration (%)					Percent to Peak Grip Aperture (%)					Peak Grip Aperture (mm)				
		Norm	$SD_{b/n}$	$SD_{w/in}$	P44	SD	Norm	$SD_{b/n}$	$SD_{w/in}$	P44	SD	Norm	$SD_{b/n}$	$SD_{w/in}$	P44	SD
M 1	R-G	55.7	8.0	7.8	40.7	15.2	73.3	6.5	6.9	34.1	57.5	116	8	8	53	0
M 2	R-G	72.6	8.6	5.6	32.7	4.9	80.1	8.0	4.6	86.3	21.9	106	10	5	67	5
M 3	R-G	72.8	8.4	5.9	35.1	7.0	81.5	4.9	5.0	83.7	18.1	109	8	5	66	2

* For all tables: standard deviations are presented as between-participant SD for normative data and between-trial SD for prosthesis user participant data unless otherwise stated. Red highlighted cells indicate prosthesis user outcomes which were more than two SD from the normative mean.
M = Movement, R = Reach, G = Grasp, T = Transport, RL = Release.

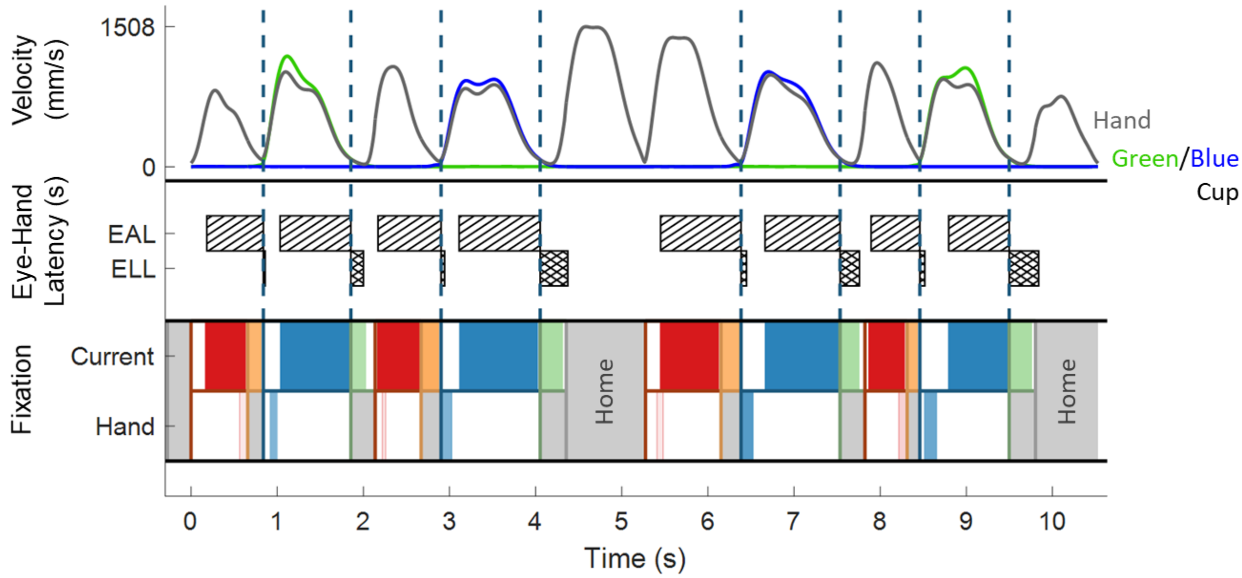
Appendix H. Detailed Report for Participant P96

Table H.1: Participant Information

Age (years)	38
Gender	Male
Level of amputation	Transhumeral
Amputation side	Left
Length of residual limb (cm)	28
Years since amputation at date of testing	10
Type of prosthesis	Body powered
Type of end-effector	Split hook, voluntary open
Hours per day of use	12
AM-ULA	Not assessed
UEFS	62.6

H.1 Cup Transfer Task Outcomes

Normative Data Set:



P96:

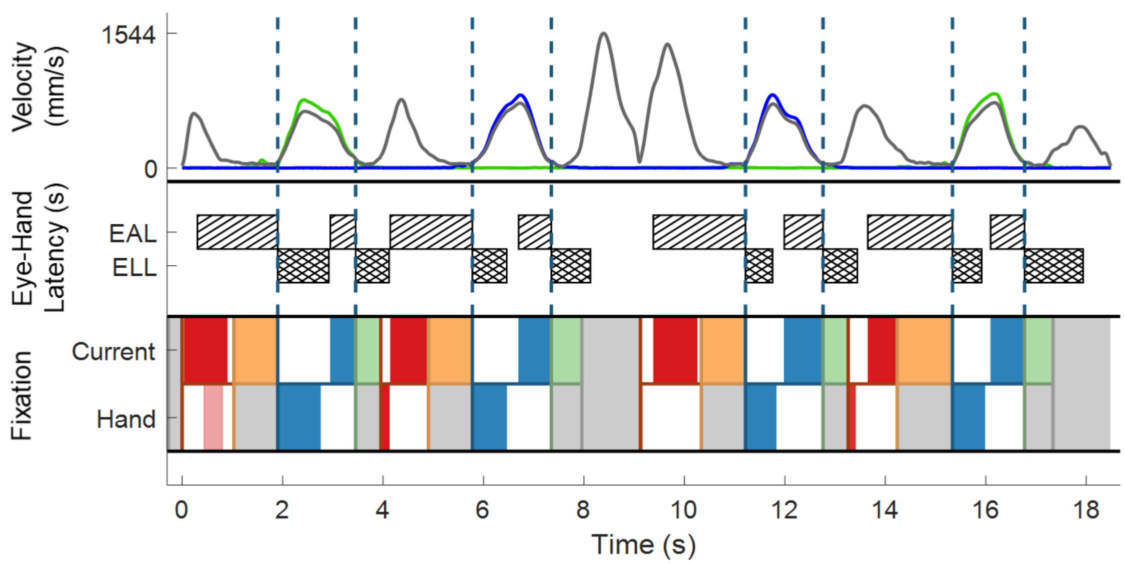


Figure H.1: Summary figures for prosthesis user participant compared with normative data. Top row: velocity plots for hand (grey) and objects (green cup and blue cup). Middle row: Eye Arrival Latencies and Eye Leaving Latencies (at Pick-Up and Drop-Off). Bottom row: fixation plots representing Percent Fixations to 'Current' and 'Hand Only' AOIs throughout each task phase: Reach (red), Grasp (orange), Transport (blue), and Release (green). Opacity level of fixation plots represents probability of fixation. The entire task is plotted with time along the x-axis.

Table H.2: Task performance

Number of successful trials	9
Trial success rate (%)	90%
Errors	1 – Hit partition
Number of trials analyzed	9

Table H.3: Phase Durations and Relative Phase Durations*

		Duration (s)				Relative Phase Duration (%)			
		Norm	SD	P96	SD	Norm	SD	P96	SD
M 1	R	0.66	0.09	1.03	0.14	30.79	1.72	26.23	2.87
	G	0.18	0.05	0.87	0.23	8.38	1.83	22.06	4.47
	T	1.02	0.10	1.55	0.19	47.77	2.42	39.46	3.53
	RL	0.28	0.07	0.50	0.23	13.06	2.34	12.25	3.90
M 2	R	0.53	0.09	0.95	0.15	24.00	1.67	23.91	2.10
	G	0.23	0.07	0.88	0.46	10.26	1.92	20.97	7.01
	T	1.15	0.12	1.57	0.21	52.15	2.72	40.05	6.42
	RL	0.30	0.07	0.61	0.17	13.59	2.88	15.07	1.68
M 3	R	0.88	0.12	1.21	0.15	34.43	2.03	29.33	2.65
	G	0.23	0.06	0.88	0.22	9.06	1.57	21.21	4.38
	T	1.15	0.12	1.54	0.20	45.30	2.42	37.30	2.60
	RL	0.29	0.09	0.50	0.14	11.21	3.00	12.16	3.16
M 4	R	0.49	0.06	0.98	0.07	24.91	2.60	24.32	3.52
	G	0.15	0.05	1.10	0.43	7.29	1.71	26.34	6.90
	T	1.04	0.12	1.44	0.17	52.57	2.65	35.49	4.45
	RL	0.31	0.09	0.57	0.14	15.23	3.74	13.85	2.61
	Total	10.53	1.32	18.49	2.45				

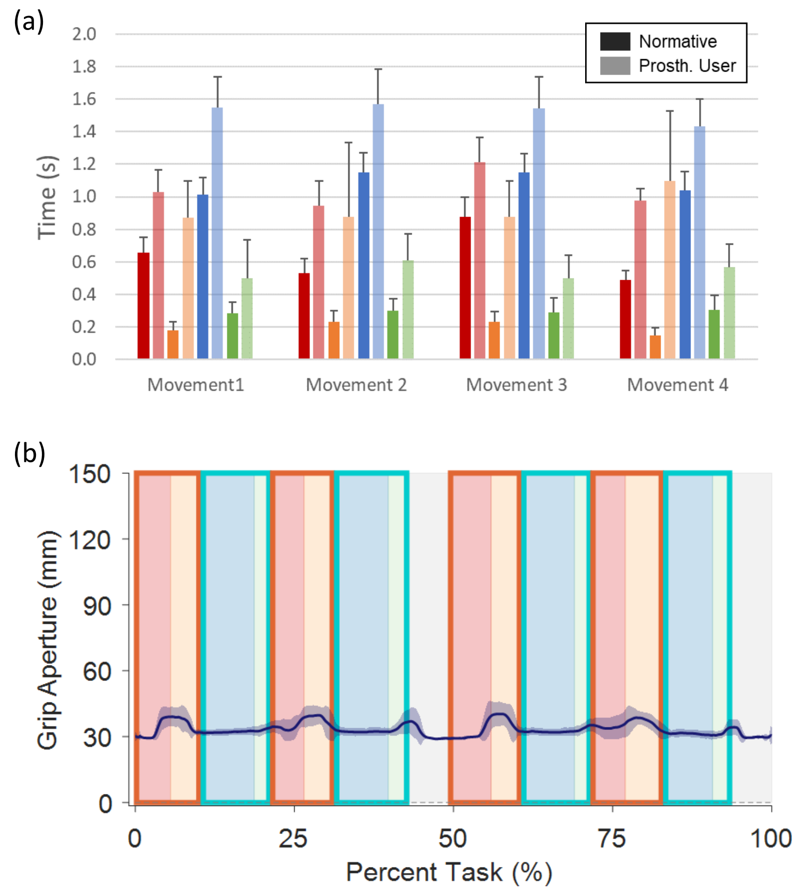


Figure H.2: (a) Phase Durations compared with normative data, (b) Grip Aperture profile. Phases are color coded: Reach (red), Grasp (orange), Transport(blue), and Release (green).

* For all tables: standard deviations are presented as between-participant SD for normative data and between-trial SD for prosthesis user participant data unless otherwise stated. Red highlighted cells indicate prosthesis user outcomes which were more than two SD from the normative mean.
M = Movement, R = Reach, G = Grasp, T = Transport, RL = Release.

Table H.4: Eye Gaze Fixation and Eye-Hand Latency Metrics*

		Mean Percent Fixations (When Fixated) (%)								Mean Number of Fixations							
		Current AOI				Hand Only AOI				Current AOI				Hand Only AOI			
		Norm	SD	P96	SD	Norm	SD	P96	SD	Norm	SD	P96	SD	Norm	SD	P96	SD
M 1	R	71.8	14.6	84.8	16.7	14.3	6.7	30.7	6.5	1.00	0.11	1.33	0.50	0.02	0.04	0.33	0.50
	G	82.5	21.3	100.0	0.0					0.89	0.16	1.00	0.00				
	T	78.8	11.4	33.0	8.2	8.2	4.8	54.4	13.8	1.02	0.03	1.00	0.00	0.52	0.32	1.78	0.67
	RL	58.0	18.2	100.0	0.0					0.87	0.18	1.00	0.00				
M 2	R	92.6	7.4	80.8	8.6	7.5	4.2	17.5	7.5	1.01	0.02	1.00	0.00	0.08	0.09	1.00	0.00
	G	86.7	13.9	100.0	0.0					0.95	0.10	1.00	0.00				
	T	79.5	11.9	41.5	3.1	10.3	4.0	42.8	7.1	1.01	0.02	1.00	0.00	0.58	0.29	1.00	0.00
	RL	82.2	16.7	98.5	4.5					0.94	0.22	1.00	0.00				
M 3	R	77.6	15.3	72.1	9.6	7.3	4.8	3.1	2.8	1.00	0.07	1.56	0.53	0.07	0.17	0.56	0.53
	G	90.4	14.5	100.0	0.0					0.90	0.24	1.00	0.00				
	T	74.5	10.7	50.0	6.7	11.8	6.1	39.3	7.8	1.03	0.05	1.00	0.00	0.74	0.33	1.89	0.33
	RL	75.7	15.3	99.0	3.1					0.94	0.15	1.00	0.00				
M 4	R	85.3	12.1	59.9	6.9	16.8	12.2	15.0	5.9	0.96	0.09	1.00	0.00	0.11	0.18	0.89	0.33
	G	78.1	21.9	100.0	0.0					0.83	0.27	1.00	0.00				
	T	66.2	14.6	47.1	2.3	13.7	9.6	44.7	6.3	0.96	0.14	1.00	0.00	0.68	0.43	1.44	0.53
	RL	82.5	18.9	100.0	0.0					0.94	0.17	1.00	0.00				

		EAL_{Grasp} (s)				EAL (s)				ELL (s)				$ELL_{Release}$ (s)			
		Norm	SD	P96	SD	Norm	SD	P96	SD	Norm	SD	P96	SD	Norm	SD	P96	SD
M 1	P	0.475	0.138	0.726	0.290	0.656	0.155	1.600	0.343	-0.020	0.103	-1.017	0.266				
	D					0.822	0.151	0.504	0.100	-0.146	0.101	-0.666	0.284	0.136	0.089	-0.164	0.086
M 2	P	0.500	0.104	0.759	0.099	0.732	0.165	1.635	0.527	-0.040	0.097	-0.684	0.187				
	D					0.941	0.119	0.650	0.091	-0.320	0.258	-0.779	0.203	-0.018	0.251	-0.170	0.086
M 3	P	0.700	0.153	0.956	0.190	0.934	0.185	1.835	0.222	-0.062	0.181	-0.540	0.228				
	D					0.870	0.160	0.771	0.140	-0.224	0.114	-0.684	0.214	0.065	0.110	-0.183	0.125
M 4	P	0.418	0.091	0.585	0.083	0.566	0.102	1.685	0.415	-0.057	0.193	-0.581	0.206				
	D					0.703	0.173	0.677	0.088	-0.341	0.190	-1.166	0.411	-0.036	0.174	-0.599	0.332

* For all tables: standard deviations are presented as between-participant SD for normative data and between-trial SD for prosthesis user participant data unless otherwise stated. Red highlighted cells indicate prosthesis user outcomes which were more than two SD from the normative mean.

M = Movement, R = Reach, G = Grasp, T = Transport, RL = Release, P = Pick-up, D = Drop-off.

Table H.5: End Effector Metrics*

		Hand Distance Travelled (mm)					Hand Trajectory Variability (mm)				Number of Movement Units				
		Norm	$SD_{b/n}$	$SD_{w/in}$	P96	SD	Norm	$SD_{b/n}$	P96	SD	Norm	$SD_{b/n}$	$SD_{w/in}$	P96	SD
M 1	R-G	366	52	23	350	33	16	3	18		1	0	0	6	1
	T-RL	646	39	21	663	19	17	4	26		2	0	1	5	2
M 2	R-G	456	56	30	468	50	17	4	27		1	0	0	4	2
	T-RL	700	46	27	694	21	20	5	29		2	0	1	4	1
M 3	R-G	887	35	25	1018	50	26	5	83		2	0	0	4	1
	T-RL	724	46	28	661	16	20	4	24		2	1	1	4	1
M 4	R-G	428	49	24	567	28	14	4	41		1	0	0	8	2
	T-RL	657	46	25	667	15	20	4	25		2	0	1	4	2

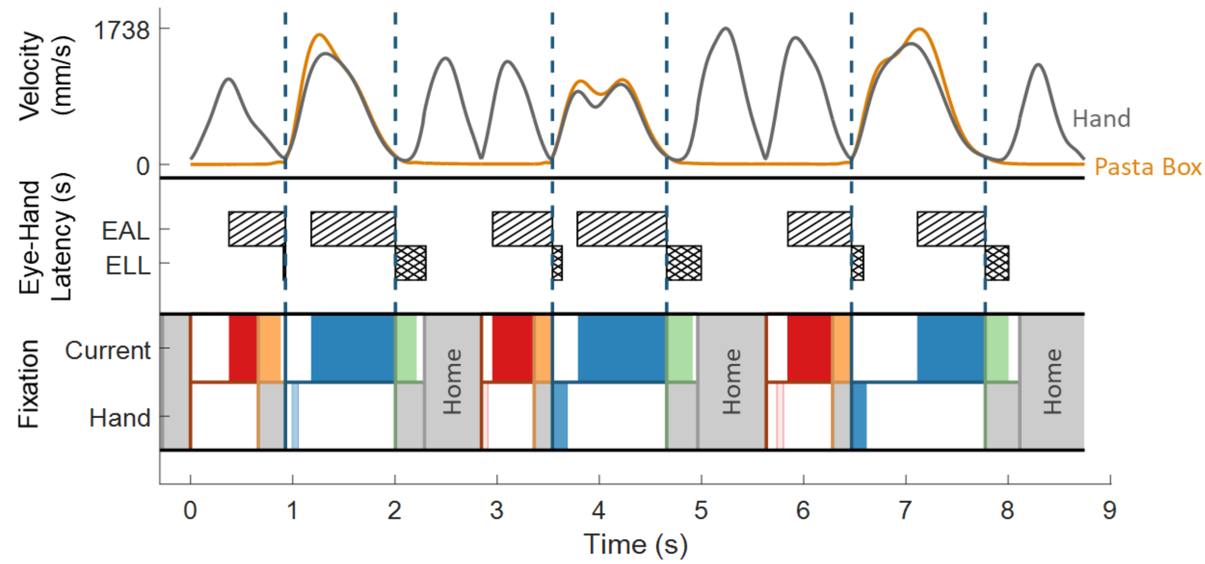
		Peak Hand Velocity (mm/s)					Percent to Peak Hand Velocity (%)				
		Norm	$SD_{b/n}$	$SD_{w/in}$	P96	SD	Norm	$SD_{b/n}$	$SD_{w/in}$	P96	SD
M 1	R-G	866	166	71	645	67	35.2	4.4	4.8	13.7	2.7
	T-RL	1042	88	52	686	88	21.0	2.6	3.0	26.4	5.2
M 2	R-G	1149	139	75	850	71	30.3	7.2	5.9	22.7	3.0
	T-RL	940	70	49	781	66	37.7	9.1	7.0	45.0	3.7
M 3	R-G	1492	187	82	1546	119	36.3	8.4	6.9	27.2	5.1
	T-RL	1009	56	52	750	38	24.7	2.4	2.8	27.5	2.8
M 4	R-G	1157	147	72	811	59	24.5	4.7	5.4	17.1	7.3
	T-RL	979	76	49	795	66	28.0	7.6	8.4	40.3	5.4

		Percent to Peak Hand Deceleration (%)					Percent to Peak Grip Aperture (%)					Peak Grip Aperture (mm)				
		Norm	$SD_{b/n}$	$SD_{w/in}$	P96	SD	Norm	$SD_{b/n}$	$SD_{w/in}$	P96	SD	Norm	$SD_{b/n}$	$SD_{w/in}$	P96	SD
M 1	R-G	62.0	8.7	13.7	27.3	6.2	80.4	4.7	5.1	55.6	11.8	99	4	3	39	2
M 2	R-G	49.8	6.5	6.9	34.8	11.2	73.0	6.3	9.1	79.8	14.7	114	6	4	38	4
M 3	R-G	61.0	5.3	5.9	35.6	8.4	80.4	3.9	4.9	67.6	6.1	114	7	2	40	3
M 4	R-G	62.3	13.5	11.8	31.8	12.9	83.7	5.4	9.2	92.1	13.4	100	5	4	34	3

* For all tables: standard deviations are presented as between-participant SD for normative data and between-trial SD for prosthesis user participant data unless otherwise stated. Red highlighted cells indicate prosthesis user outcomes which were more than two SD from the normative mean.
M = Movement, R = Reach, G = Grasp, T = Transport, RL = Release.

H.2 Pasta Box Task Outcomes

Normative Data Set:



P96:

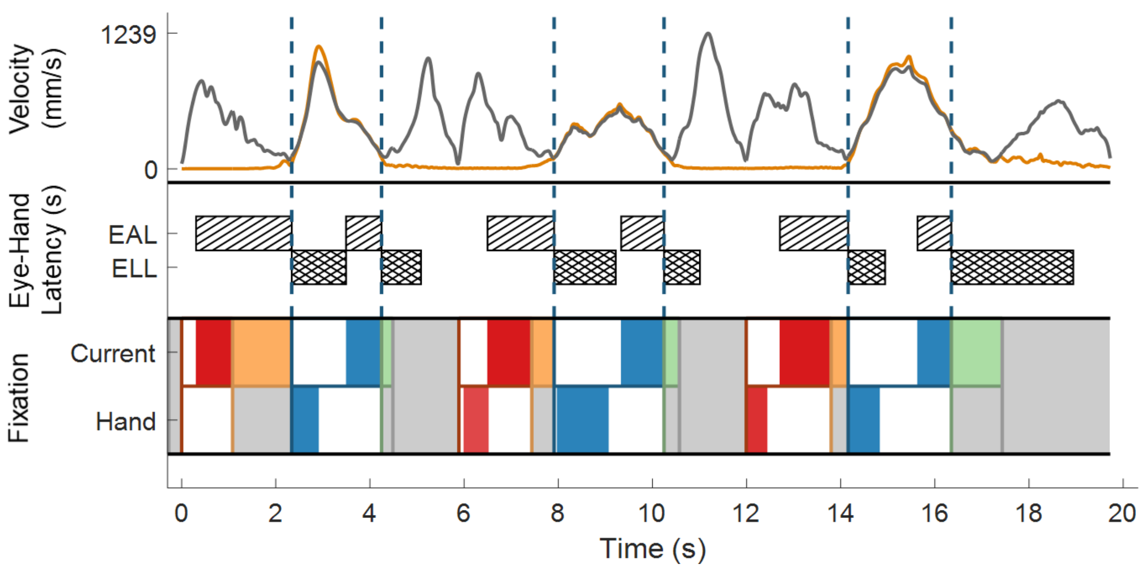


Figure H.3: Summary figures for prosthesis user participant compared with normative data. Top row: velocity plots for hand (grey) and objects (green cup and blue cup). Middle row: Eye Arrival Latencies and Eye Leaving Latencies (at Pick-Up and Drop-Off). Bottom row: fixation plots representing Percent Fixations to 'Current' and 'Hand Only' AOIs throughout each task phase: Reach (red), Grasp (orange), Transport (blue), and Release (green). Opacity level of fixation plots represents probability of fixation. The entire task is plotted with time along the x-axis.

Table H.6: Task performance

Number of successful trials	8
Trial success rate (%)	73%
Errors	2 – Dropped box
	1 – Incorrect sequence
Number of trials analyzed	8

Table H.7: Phase Durations and Relative Phase Durations*

		Duration (s)				Relative Phase Duration (%)			
		Norm	SD	P96	SD	Norm	SD	P96	SD
M 1	R	0.66	0.08	1.08	0.51	29.03	2.01	24.26	9.34
	G	0.27	0.08	1.26	0.73	11.47	2.47	26.73	11.98
	T	1.08	0.12	1.91	0.18	47.13	2.22	43.56	6.01
	RL	0.28	0.07	0.24	0.11	12.37	2.34	5.45	2.27
M 2	R	0.52	0.06	1.55	0.89	24.44	2.01	33.93	16.89
	G	0.18	0.05	0.47	0.36	8.32	1.67	9.89	5.21
	T	1.12	0.13	2.33	1.01	53.00	2.89	49.63	12.99
	RL	0.30	0.08	0.33	0.19	14.24	2.73	6.55	2.51
M 3	R	0.65	0.10	1.80	0.79	26.18	1.82	33.16	12.98
	G	0.19	0.06	0.36	0.16	7.36	1.78	6.58	2.72
	T	1.31	0.16	2.19	0.37	52.91	2.07	41.77	11.80
	RL	0.34	0.07	1.08	0.97	13.56	2.16	18.49	14.86
Total		8.75	1.20	19.73	2.97				

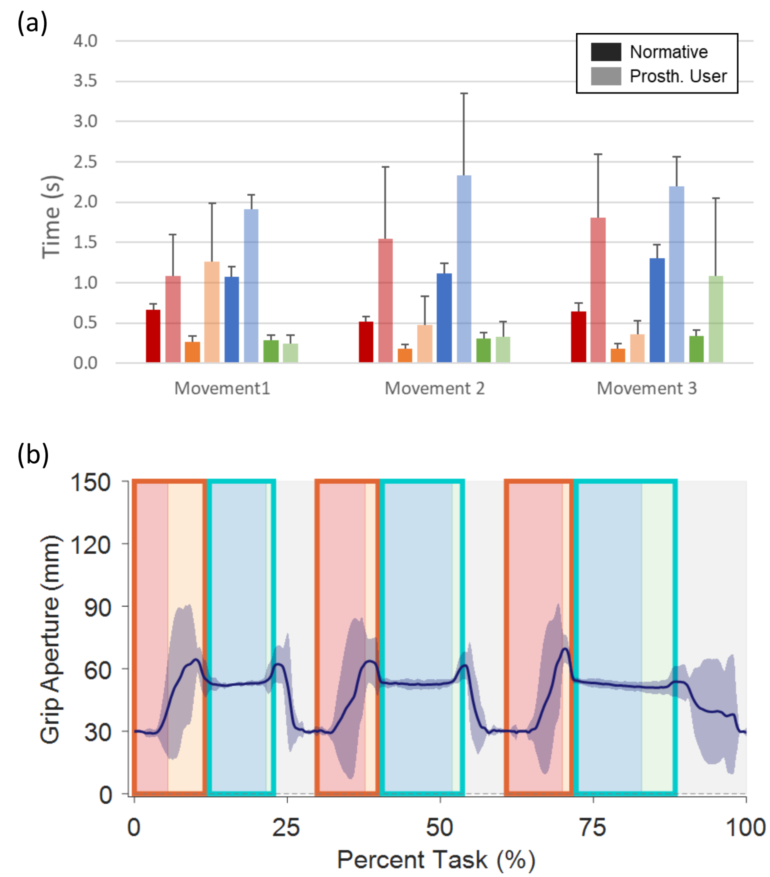


Figure H.4: (a) Phase Durations compared with normative data, (b) Grip Aperture profile. Phases are color coded: Reach (red), Grasp (orange), Transport(blue), and Release (green).

* For all tables: standard deviations are presented as between-participant SD for normative data and between-trial SD for prosthesis user participant data unless otherwise stated. Red highlighted cells indicate prosthesis user outcomes which were more than two SD from the normative mean.
M = Movement, R = Reach, G = Grasp, T = Transport, RL = Release.

Table H.8: Eye Gaze Fixation and Eye-Hand Latency Metrics*

		Mean Percent Fixations (When Fixated) (%)								Mean Number of Fixations							
		Current AOI				Hand Only AOI				Current AOI				Hand Only AOI			
		Norm	SD	P96	SD	Norm	SD	P96	SD	Norm	SD	P96	SD	Norm	SD	P96	SD
M 1	R	42.8	8.6	66.7	15.1	0.0	0.0	0.0	0.0	1.01	0.14	1.00	0.00	0.00	0.00	0.00	0.00
	G	82.7	15.0	100.0	0.0					0.97	0.07	1.00	0.00				
	T	75.1	9.7	39.7	7.3	5.8	2.4	29.7	8.1	1.03	0.05	1.00	0.00	0.32	0.33	2.13	0.35
	RL	71.8	18.0	100.0	0.0					0.99	0.03	1.00	0.00				
M 2	R	77.5	15.0	71.3	23.6	10.5	9.0	23.2	16.5	1.00	0.02	1.00	0.00	0.03	0.10	0.75	0.89
	G	89.4	15.3	100.0	0.0					0.93	0.15	1.00	0.00				
	T	76.9	9.3	42.7	10.5	12.7	6.7	43.4	14.7	1.02	0.06	1.00	0.00	0.75	0.28	1.63	0.52
	RL	81.8	15.1	100.0	0.0					0.99	0.03	1.00	0.00				
M 3	R	66.4	15.8	63.9	16.2	10.5	7.7	20.1	13.4	1.02	0.04	1.00	0.00	0.07	0.19	0.88	0.64
	G	93.6	14.0	100.0	0.0					0.98	0.05	1.00	0.00				
	T	50.0	4.7	32.1	7.5	11.2	3.6	29.6	12.8	1.06	0.09	1.00	0.00	0.85	0.27	1.75	0.71
	RL	64.2	15.8	100.0	0.0					1.00	0.09	1.00	0.00				

		EAL_{Grasp} (s)				EAL (s)				ELL (s)				$ELL_{Release}$ (s)			
		Norm	SD	P96	SD	Norm	SD	P96	SD	Norm	SD	P96	SD	Norm	SD	P96	SD
M 1	P	0.286	0.068	0.775	0.512	0.552	0.114	2.032	0.778	0.019	0.078	-1.154	0.192				
	D					0.823	0.200	0.753	0.121	-0.297	0.201	-0.839	0.202	-0.013	0.188	-0.598	0.206
M 2	P	0.405	0.106	0.941	0.380	0.584	0.141	1.415	0.233	-0.094	0.129	-1.310	1.090				
	D					0.873	0.171	0.909	0.121	-0.338	0.188	-0.762	0.220	-0.034	0.168	-0.435	0.140
M 3	P	0.437	0.134	1.088	0.423	0.623	0.174	1.449	0.487	-0.116	0.091	-0.786	0.387				
	D					0.662	0.100	0.718	0.282	-0.229	0.095	-2.590	1.354	0.109	0.065	-1.509	1.679

* For all tables: standard deviations are presented as between-participant SD for normative data and between-trial SD for prosthesis user participant data unless otherwise stated. Red highlighted cells indicate prosthesis user outcomes which were more than two SD from the normative mean.
M = Movement, R = Reach, G = Grasp, T = Transport, RL = Release, P = Pick-up, D = Drop-off.

Table H.9: End Effector Metrics*

		Hand Distance Travelled (mm)					Hand Trajectory Variability (mm)				Number of Movement Units				
		Norm	$SD_{b/n}$	$SD_{w/in}$	P96	SD	Norm	$SD_{b/n}$	P96	SD	Norm	$SD_{b/n}$	$SD_{w/in}$	P96	SD
M 1	R-G	492	26	23	937	492	19	5	85		1	0	0	7	3
	T-RL	935	27	16	960	32	22	4	56		1	0	0	4	1
M 2	R-G	505	23	19	803	321	15	5	97		1	0	0	6	3
	T-RL	802	61	24	846	174	20	4	79		2	0	0	7	5
M 3	R-G	746	24	14	940	299	19	4	135		1	0	0	7	4
	T-RL	1186	31	18	1468	212	35	8	202		2	0	1	8	4

		Peak Hand Velocity (mm/s)					Percent to Peak Hand Velocity (%)				
		Norm	$SD_{b/n}$	$SD_{w/in}$	P96	SD	Norm	$SD_{b/n}$	$SD_{w/in}$	P96	SD
M 1	R-G	1164	163	90	985	238	41.2	4.5	3.0	29.7	11.3
	T-RL	1447	136	81	1016	88	29.3	3.1	3.0	26.8	3.7
M 2	R-G	1352	191	64	1118	104	36.8	4.4	3.5	26.2	15.9
	T-RL	1069	112	55	604	41	44.8	8.6	10.5	48.2	13.8
M 3	R-G	1666	261	92	1224	232	35.5	4.0	3.6	37.3	17.1
	T-RL	1598	180	106	1228	248	36.2	3.8	3.8	40.4	10.0

		Percent to Peak Hand Deceleration (%)					Percent to Peak Grip Aperture (%)					Peak Grip Aperture (mm)				
		Norm	$SD_{b/n}$	$SD_{w/in}$	P96	SD	Norm	$SD_{b/n}$	$SD_{w/in}$	P96	SD	Norm	$SD_{b/n}$	$SD_{w/in}$	P96	SD
M 1	R-G	55.7	8.0	7.8	44.0	23.6	73.3	6.5	6.9	70.6	30.3	116	8	8	68	3
M 2	R-G	72.6	8.6	5.6	34.2	9.9	80.1	8.0	4.6	66.8	30.1	106	10	5	68	2
M 3	R-G	72.8	8.4	5.9	34.5	21.6	81.5	4.9	5.0	72.3	29.9	109	8	5	70	3

* For all tables: standard deviations are presented as between-participant SD for normative data and between-trial SD for prosthesis user participant data unless otherwise stated. Red highlighted cells indicate prosthesis user outcomes which were more than two SD from the normative mean.
M = Movement, R = Reach, G = Grasp, T = Transport, RL = Release.

Appendix I. Detailed Report for Participant P03

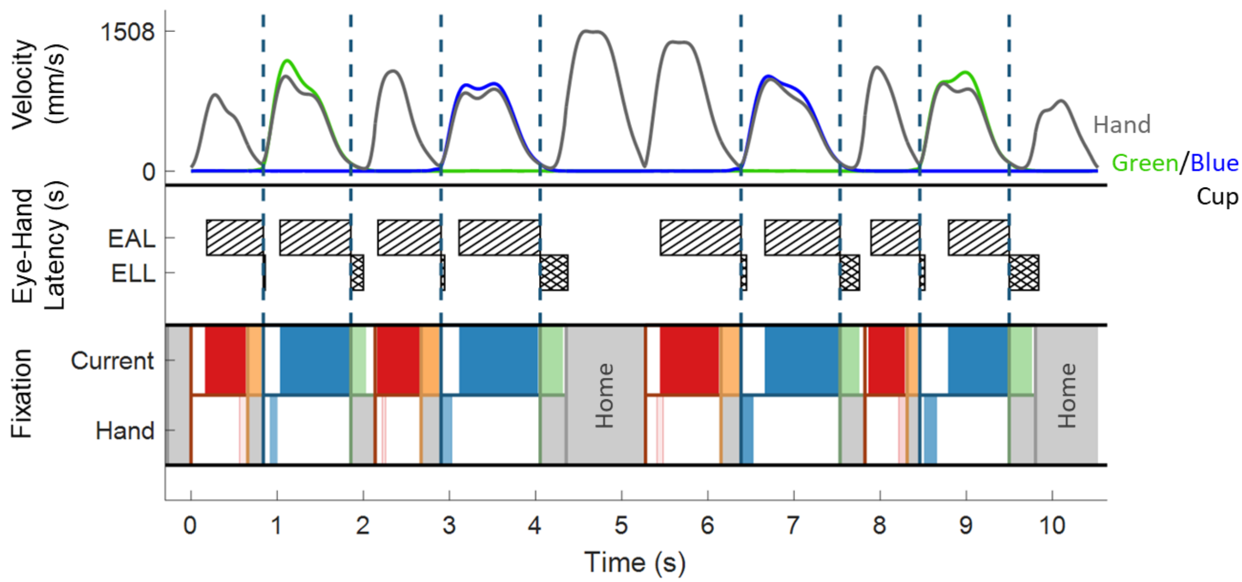
Table I.1: Participant Information

Age (years)	54
Gender	Female
Level of amputation	Transhumeral
Amputation side	Left
Length of residual limb (cm)	22
Years since amputation at date of testing	10
hType of prosthesis	Body powered
Type of end-effector	Split hook, voluntary open
Hours per day of use	2
AM-ULA	12.2
UEFS	56.8

* Note that P03's gaze vector for the Cup Transfer task was not reliable. Eye gaze metrics are not reported

I.1 Cup Transfer Task Outcomes

Normative Data Set:



P03:

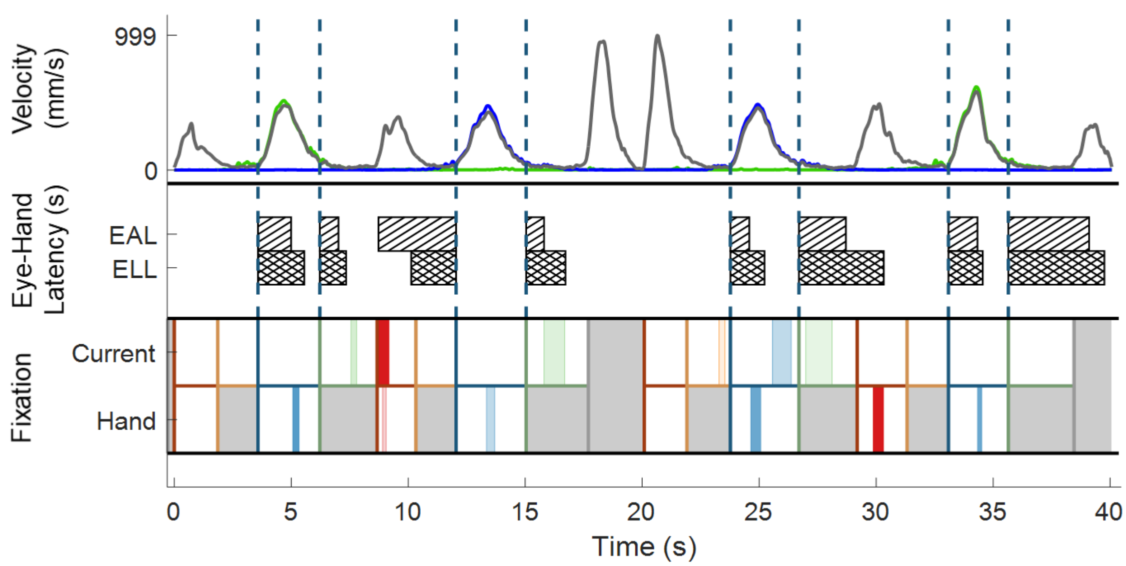


Figure I.1: Summary figures for prosthesis user participant compared with normative data. Top row: velocity plots for hand (grey) and objects (green cup and blue cup). Middle row: Eye Arrival Latencies and Eye Leaving Latencies (at Pick-Up and Drop-Off). Bottom row: fixation plots representing Percent Fixations to 'Current' and 'Hand Only' AOIs throughout each task phase: Reach (red), Grasp (orange), Transport (blue), and Release (green). Opacity level of fixation plots represents probability of fixation. The entire task is plotted with time along the x-axis.

Table I.2: Task performance

Number of successful trials	9
Trial success rate (%)	90%
Errors	1 – Hit partition
Number of trials analyzed	9

Table I.3: Phase Durations and Relative Phase Durations*

		Duration (s)				Relative Phase Duration (%)			
		Norm	SD	P03	SD	Norm	SD	P03	SD
M 1	R	0.66	0.09	1.86	0.21	30.79	1.72	21.81	4.13
	G	0.18	0.05	1.72	0.63	8.38	1.83	19.48	5.45
	T	1.02	0.10	2.64	0.31	47.77	2.42	30.57	2.85
	RL	0.28	0.07	2.45	0.57	13.06	2.34	28.14	4.90
M 2	R	0.53	0.09	1.66	0.19	24.00	1.67	18.46	2.27
	G	0.23	0.07	1.72	0.56	10.26	1.92	18.68	4.32
	T	1.15	0.12	2.99	0.34	52.15	2.72	33.29	3.10
	RL	0.30	0.07	2.66	0.34	13.59	2.88	29.56	3.17
M 3	R	0.88	0.12	1.82	0.16	34.43	2.03	20.24	2.48
	G	0.23	0.06	1.86	0.55	9.06	1.57	20.18	4.67
	T	1.15	0.12	2.93	0.37	45.30	2.42	32.51	4.81
	RL	0.29	0.09	2.49	0.74	11.21	3.00	27.07	5.86
M 4	R	0.49	0.06	2.13	0.16	24.91	2.60	23.11	2.28
	G	0.15	0.05	1.77	0.75	7.29	1.71	18.79	6.68
	T	1.04	0.12	2.56	0.24	52.57	2.65	27.78	3.34
	RL	0.31	0.09	2.81	0.47	15.23	3.74	30.31	4.54
Total		10.53	1.32	40.07	2.58				

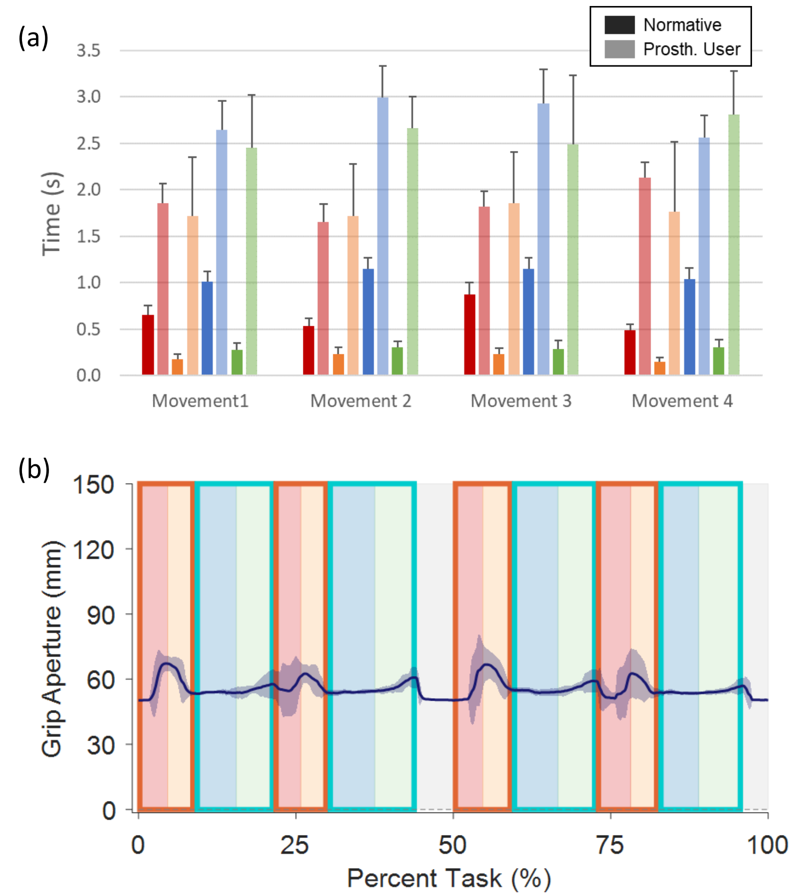


Figure I.2: (a) Phase Durations compared with normative data, (b) Grip Aperture profile. Phases are color coded: Reach (red), Grasp (orange), Transport(blue), and Release (green).

* For all tables: standard deviations are presented as between-participant SD for normative data and between-trial SD for prosthesis user participant data unless otherwise stated. Red highlighted cells indicate prosthesis user outcomes which were more than two SD from the normative mean.
M = Movement, R = Reach, G = Grasp, T = Transport, RL = Release.

Table I.4: Eye Gaze Fixation and Eye-Hand Latency Metrics*

* Note that P03's gaze vector for the Cup Transfer task was not reliable. Eye gaze metrics are not reported

Table I.5: End Effector Metrics*

		Hand Distance Travelled (mm)					Hand Trajectory Variability (mm)				Number of Movement Units				
		Norm	SD$_{b/n}$	SD$_{w/in}$	P03	SD	Norm	SD$_{b/n}$	P03	SD	Norm	SD$_{b/n}$	SD$_{w/in}$	P03	SD
M 1	R-G	366	52	23	358	21	16	3	23		1	0	0	16	4
	T-RL	646	39	21	754	48	17	4	40		2	0	1	21	4
M 2	R-G	456	56	30	488	34	17	4	36		1	0	0	12	4
	T-RL	700	46	27	727	40	20	5	52		2	0	1	22	3
M 3	R-G	887	35	25	919	67	26	5	56		2	0	0	14	4
	T-RL	724	46	28	722	27	20	4	44		2	1	1	23	6
M 4	R-G	428	49	24	613	42	14	4	46		1	0	0	15	3
	T-RL	657	46	25	766	49	20	4	35		2	0	1	23	4

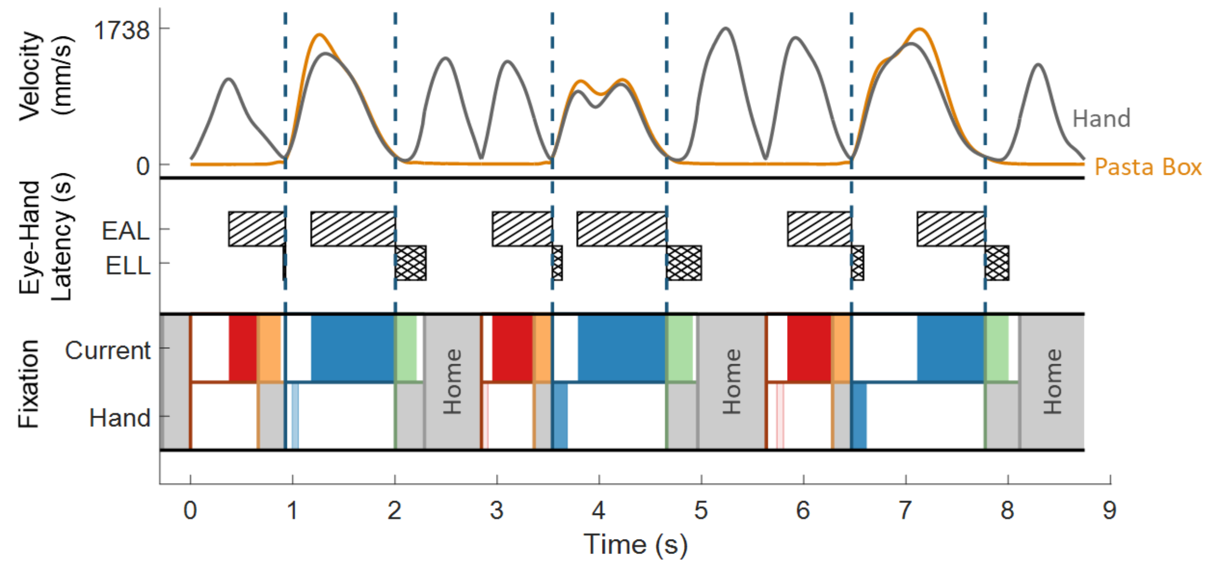
		Peak Hand Velocity (mm/s)					Percent to Peak Hand Velocity (%)				
		Norm	SD$_{b/n}$	SD$_{w/in}$	P03	SD	Norm	SD$_{b/n}$	SD$_{w/in}$	P03	SD
M 1	R-G	866	166	71	415	75	35.2	4.4	4.8	19.3	3.1
	T-RL	1042	88	52	539	66	21.0	2.6	3.0	22.7	3.1
M 2	R-G	1149	139	75	458	32	30.3	7.2	5.9	24.0	6.1
	T-RL	940	70	49	524	74	37.7	9.1	7.0	26.4	5.3
M 3	R-G	1492	187	82	1088	127	36.3	8.4	6.9	17.2	3.4
	T-RL	1009	56	52	508	66	24.7	2.4	2.8	21.3	4.7
M 4	R-G	1157	147	72	611	136	24.5	4.7	5.4	22.2	5.5
	T-RL	979	76	49	617	61	28.0	7.6	8.4	23.1	2.5

		Percent to Peak Hand Deceleration (%)					Percent to Peak Grip Aperture (%)					Peak Grip Aperture (mm)				
		Norm	SD$_{b/n}$	SD$_{w/in}$	P03	SD	Norm	SD$_{b/n}$	SD$_{w/in}$	P03	SD	Norm	SD$_{b/n}$	SD$_{w/in}$	P03	SD
M 1	R-G	62.0	8.7	13.7	22.1	3.4	80.4	4.7	5.1	54.8	10.8	99	4	3	67	2
M 2	R-G	49.8	6.5	6.9	25.5	13.2	73.0	6.3	9.1	77.2	20.0	114	6	4	60	5
M 3	R-G	61.0	5.3	5.9	24.5	8.1	80.4	3.9	4.9	55.6	8.8	114	7	2	67	4
M 4	R-G	62.3	13.5	11.8	31.3	6.4	83.7	5.4	9.2	61.9	15.9	100	5	4	63	5

* For all tables: standard deviations are presented as between-participant SD for normative data and between-trial SD for prosthesis user participant data unless otherwise stated. Red highlighted cells indicate prosthesis user outcomes which were more than two SD from the normative mean.
M = Movement, R = Reach, G = Grasp, T = Transport, RL = Release.

I.2 Pasta Box Task Outcomes

Normative Data Set:



P03:

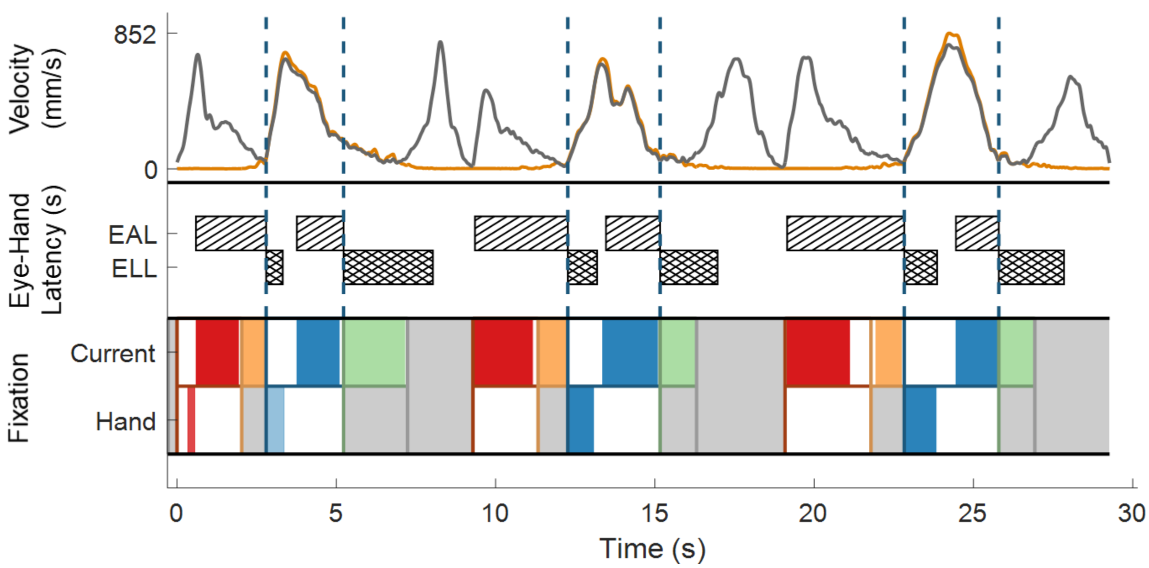


Figure I.3: Summary figures for prosthesis user participant compared with normative data. Top row: velocity plots for hand (grey) and objects (green cup and blue cup). Middle row: Eye Arrival Latencies and Eye Leaving Latencies (at Pick-Up and Drop-Off). Bottom row: fixation plots representing Percent Fixations to 'Current' and 'Hand Only' AOIs throughout each task phase: Reach (red), Grasp (orange), Transport (blue), and Release (green). Opacity level of fixation plots represents probability of fixation. The entire task is plotted with time along the x-axis.

Table I.6: Task performance

Number of successful trials	8
Trial success rate (%)	80%
Errors	2 – Placed incorrectly
Number of trials analyzed	8

Table I.7: Phase Durations and Relative Phase Durations*

		Duration (s)				Relative Phase Duration (%)			
		Norm	SD	P03	SD	Norm	SD	P03	SD
M 1	R	0.66	0.08	2.03	0.16	29.03	2.01	28.56	4.33
	G	0.27	0.08	0.77	0.19	11.47	2.47	10.95	3.79
	T	1.08	0.12	2.43	0.26	47.13	2.22	34.44	7.28
	RL	0.28	0.07	2.01	1.30	12.37	2.34	26.06	14.25
M 2	R	0.52	0.06	2.05	0.15	24.44	2.01	29.55	4.11
	G	0.18	0.05	0.93	0.38	8.32	1.67	12.95	4.00
	T	1.12	0.13	2.90	0.46	53.00	2.89	41.34	4.28
	RL	0.30	0.08	1.14	0.39	14.24	2.73	16.16	4.40
M 3	R	0.65	0.10	2.70	0.42	26.18	1.82	34.99	6.28
	G	0.19	0.06	1.05	0.90	7.36	1.78	12.25	7.47
	T	1.31	0.16	2.97	0.60	52.91	2.07	38.09	6.26
	RL	0.34	0.07	1.13	0.23	13.56	2.16	14.67	3.30
Total		8.75	1.20	29.27	2.24				

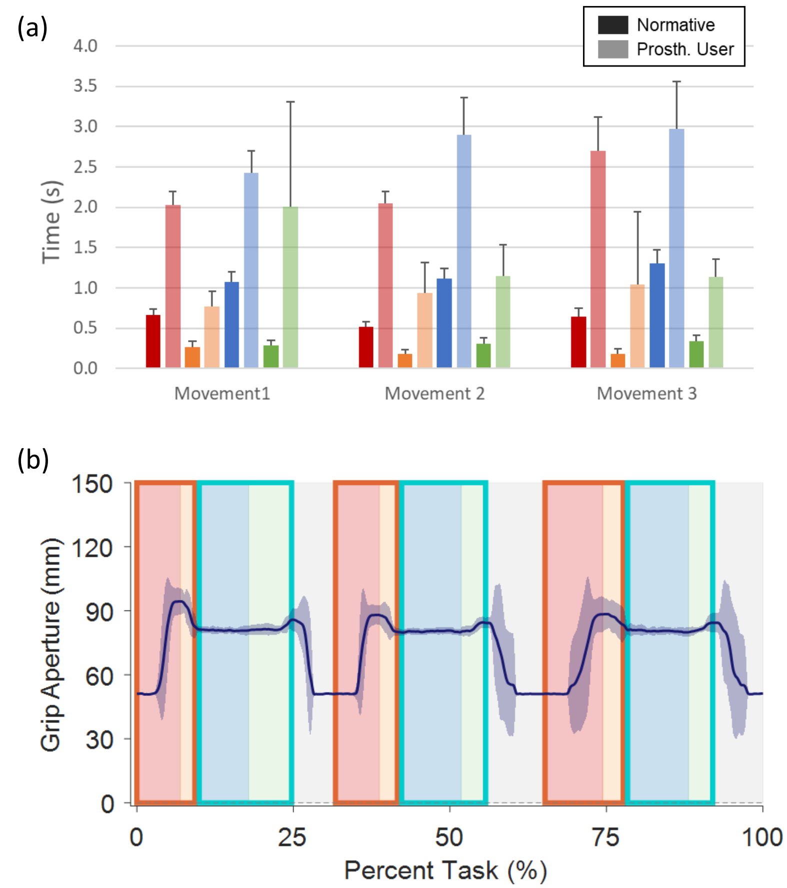


Figure I.4: (a) Phase Durations compared with normative data, (b) Grip Aperture profile. Phases are color coded: Reach (red), Grasp (orange), Transport(blue), and Release (green).

* For all tables: standard deviations are presented as between-participant SD for normative data and between-trial SD for prosthesis user participant data unless otherwise stated. Red highlighted cells indicate prosthesis user outcomes which were more than two SD from the normative mean.
M = Movement, R = Reach, G = Grasp, T = Transport, RL = Release.

Table I.8: Eye Gaze Fixation and Eye-Hand Latency Metrics*

		Mean Percent Fixations (When Fixated) (%)								Mean Number of Fixations							
		Current AOI				Hand Only AOI				Current AOI				Hand Only AOI			
		Norm	SD	P03	SD	Norm	SD	P03	SD	Norm	SD	P03	SD	Norm	SD	P03	SD
M 1	R	42.8	8.6	65.5	6.5	0.0	0.0	10.4	4.4	1.01	0.14	1.63	0.52	0.00	0.00	0.75	0.46
	G	82.7	15.0	100.0	0.0					0.97	0.07	1.00	0.00				
	T	75.1	9.7	55.0	9.6	5.8	2.4	21.0	10.6	1.03	0.05	1.38	0.52	0.32	0.33	0.50	0.53
	RL	71.8	18.0	97.7	6.5					0.99	0.03	1.13	0.35				
M 2	R	77.5	15.0	89.0	12.9	10.5	9.0	0.0	0.0	1.00	0.02	1.50	0.53	0.03	0.10	0.00	0.00
	G	89.4	15.3	95.1	13.7					0.93	0.15	1.00	0.00				
	T	76.9	9.3	59.7	8.9	12.7	6.7	27.2	10.4	1.02	0.06	1.25	0.46	0.75	0.28	1.50	0.76
	RL	81.8	15.1	95.8	11.8					0.99	0.03	1.00	0.00				
M 3	R	66.4	15.8	73.2	13.6	10.5	7.7	0.0	0.0	1.02	0.04	2.63	1.06	0.07	0.19	0.00	0.00
	G	93.6	14.0	78.4	25.9					0.98	0.05	1.25	0.71				
	T	50.0	4.7	45.7	5.2	11.2	3.6	31.6	14.6	1.06	0.09	1.00	0.00	0.85	0.27	1.25	0.71
	RL	64.2	15.8	96.7	9.3					1.00	0.09	1.00	0.00				

		EAL$_{Grasp}$ (s)				EAL (s)				ELL (s)				ELL$_{Release}$ (s)			
		Norm	SD	P03	SD	Norm	SD	P03	SD	Norm	SD	P03	SD	Norm	SD	P03	SD
M 1	P	0.286	0.068	1.435	0.208	0.552	0.114	2.203	0.264	0.019	0.078	-0.520	0.227				
	D					0.823	0.200	1.466	0.168	-0.297	0.201	-2.803	1.371	-0.013	0.188	-0.796	0.381
M 2	P	0.405	0.106	1.981	0.138	0.584	0.141	2.913	0.438	-0.094	0.129	-0.919	0.356				
	D					0.873	0.171	1.700	0.482	-0.338	0.188	-1.805	0.555	-0.034	0.168	-0.661	0.421
M 3	P	0.437	0.134	2.630	0.464	0.623	0.174	3.676	1.045	-0.116	0.091	-1.029	0.556				
	D					0.662	0.100	1.345	0.252	-0.229	0.095	-2.048	0.498	0.109	0.065	-0.917	0.480

* For all tables: standard deviations are presented as between-participant SD for normative data and between-trial SD for prosthesis user participant data unless otherwise stated. Red highlighted cells indicate prosthesis user outcomes which were more than two SD from the normative mean.
M = Movement, R = Reach, G = Grasp, T = Transport, RL = Release, P = Pick-up, D = Drop-off.

Table I.9: End Effector Metrics*

		Hand Distance Travelled (mm)					Hand Trajectory Variability (mm)				Number of Movement Units				
		Norm	SDb/n	SDw/in	P03	SD	Norm	SDb/n	P03	SD	Norm	SDb/n	SDw/in	P03	SD
M 1	R-G	492	26	23	730	53	19	5	29		1	0	0	8	1
	T-RL	935	27	16	1142	85	22	4	152		1	0	0	15	6
M 2	R-G	505	23	19	555	25	15	5	27		1	0	0	12	2
	T-RL	802	61	24	1036	110	20	4	42		2	0	0	11	3
M 3	R-G	746	24	14	950	61	19	4	70		1	0	0	16	6
	T-RL	1186	31	18	1340	54	35	8	99		2	0	1	12	2

		Peak Hand Velocity (mm/s)					Percent to Peak Hand Velocity (%)				
		Norm	SDb/n	SDw/in	P03	SD	Norm	SDb/n	SDw/in	P03	SD
M 1	R-G	1164	163	90	783	121	41.2	4.5	3.0	24.2	2.4
	T-RL	1447	136	81	993	102	29.3	3.1	3.0	21.5	9.9
M 2	R-G	1352	191	64	544	50	36.8	4.4	3.5	17.0	5.0
	T-RL	1069	112	55	696	124	44.8	8.6	10.5	27.8	2.5
M 3	R-G	1666	261	92	875	128	35.5	4.0	3.6	19.0	4.5
	T-RL	1598	180	106	876	76	36.2	3.8	3.8	33.2	9.1

		Percent to Peak Hand Deceleration (%)					Percent to Peak Grip Aperture (%)					Peak Grip Aperture (mm)				
		Norm	SDb/n	SDw/in	P03	SD	Norm	SDb/n	SDw/in	P03	SD	Norm	SDb/n	SDw/in	P03	SD
M 1	R-G	55.7	8.0	7.8	28.0	2.8	73.3	6.5	6.9	74.7	8.4	116	8	8	95	3
M 2	R-G	72.6	8.6	5.6	29.9	7.8	80.1	8.0	4.6	59.4	8.6	106	10	5	89	2
M 3	R-G	72.8	8.4	5.9	37.3	17.5	81.5	4.9	5.0	68.1	14.0	109	8	5	89	4

* For all tables: standard deviations are presented as between-participant SD for normative data and between-trial SD for prosthesis user participant data unless otherwise stated. Red highlighted cells indicate prosthesis user outcomes which were more than two SD from the normative mean.
M = Movement, R = Reach, G = Grasp, T = Transport, RL = Release.