Reproducibility and Application of the Gaze and Movement Assessment (GaMA)

by

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A thesis submitted in partial fulfillment of the requirements for the degree of

Master of Science

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Abstract

Introduction: State-of-the-art upper limb prosthetic devices are complex, with multi-articulating hands that can open and close on user command. These so-called myoelectric prostheses harness the signals of a user's residual muscles to trigger a desired function, such as grasping an object. Despite functional advancements, myoelectric prostheses still have limited dexterity and lack sensory feedback. As such, users exhibit compensatory arm and trunk movements and allocate increased visual attention during device-object interactions. A standardized and quantitative measurement protocol that assesses the movement quality of prosthetic device users has yet to be adopted by researchers and clinicians, despite the motivation to improve function. One method of evaluating upper limb function, with relevance to prosthesis use, is through assessment of hand movement, angular joint kinematics, and eye gaze measures. These measures can be derived from data that are commonly collected using optical motion capture and eye tracking technologies. Motion capture data can be used to analyze upper limb motion and hand-object interactions, and simultaneously collected eye tracking data can facilitate analysis of hand-eye coordination. Assessments reliant on specialized data capture technologies such as these, however, lack standardized protocols, are not necessarily generalizable to activities of daily living (ADLs), and risk becoming obsolete.

Background: A collaborative group of researchers at the University of Alberta has developed the Gaze and Movement Assessment (GaMA) protocol to address the need for standardized outcome performance measures that are representative of ADLs and achievable by individuals both with and without upper limb mobility restrictions. GaMA encompasses two standardized functional upper limb tasks and analysis software. This software requires a standardized data set of synchronized motion and eye data coordinates as input, and outputs hand movement, angular joint kinematic, and eye gaze measures. Although GaMA's input has been collected using optical motion capture and state-of-the-art eye tracking technologies, the protocol is amenable to future advances in data capture solutions.

Objectives: The first objective of this thesis was to determine if GaMA is reproducible – that is, whether GaMA could be used to obtain the same hand movement, angular joint kinematic, and eye gaze measures when testing two independent groups of non-disabled participants, at different research sites equipped with different data capture technologies, and by different raters. With the reproducibility of GaMA established, the second objective of this thesis was to use this assessment protocol to test the assumption that movement measures from actual myoelectric users are comparable to those of non-disabled individuals wearing a simulated prosthetic device.

Methods: To accomplish the first objective, twenty non-disabled adults performed GaMA's two functional tasks: the Pasta Box Transfer Task, which required participants to move a box of pasta to shelves of different heights; and the Cup Transfer Task, which required the same participants to move deformable, filled cups over a partition at table-top height. Participants' upper body and eye movements were recorded using optical motion capture and eye tracking technologies, respectively. GaMA's analysis software provided measures of hand movement, angular joint kinematics, and eye gaze. These measures were then compared to those from twenty non-disabled adults who had previously performed GaMA's functional tasks at a different site.

To accomplish the second objective of this thesis, three participants completed GaMA's Pasta Box Transfer Task using their custom-fitted myoelectric prosthesis. Motion capture methods were followed for data acquisition, and GaMA's software was used to derive hand movement and angular joint kinematic measures. Resulting performance metrics, end effector movements, and angular kinematics were compared to those from an already established data set, collected from twelve non-disabled participants wearing a simulated prosthesis at a different site.

Results: The research conducted in this thesis concluded that GaMA is reproducible and can serve as a quantitative assessment tool for individuals both with and without sensory-motor impairment of the upper limb. Furthermore, it supports the notion that non-disabled individuals wearing a simulated prosthesis can act as substitutes for actual prosthesis users in research and expands the potential to compare data sets across different sites.

Recommendation: Given that GaMA has been shown to be reproducible, it should be promoted as a measurement protocol for use in ongoing upper limb prosthesis research, inter-site research comparisons, and considered as a means of merging data sets to overcome sample size limitations of research participants with amputations.

Preface

This thesis is an original work by Heather E. Williams. The research project, of which this thesis is a part of, received research ethics approval from the University of Alberta Health Research Ethics Board (Pro00054011), the Department of the Navy Human Research Protection Program, and the SSC-Pacific Human Research Protection Office.

This thesis contains information published in two manuscripts currently submitted or in preparation:

The majority of Chapter 3 has been submitted as:

H.E. Williams, C.S. Chapman, P.M. Pilarski, A.H. Vette, J.S. Hebert, "Gaze and Movement Assessment (GaMA): Inter-site Validation of a Visuomotor Upper Limb Functional Protocol," *submitted to PLoS One.*

> Contributed as first author: conceptualized the study (together with A.H. Vette and J.S. Hebert), adapted the experimental protocols, scheduled human participants, collected and analyzed the experimental data, generated the figures and tables, wrote the draft manuscripts for co-author review.

The majority of Chapter 4 will be submitted as:

H.E. Williams, A.H. Vette, J.S. Hebert, "Do the movement strategies of non-disabled individuals wearing a simulated prosthesis mimic those of myoelectric device users?"

> Contributed as first author: conceptualized the study (together with J.S. Hebert and A.H. Vette), adapted the experimental protocols, analyzed the experimental data, generated the figures and tables, wrote the draft manuscripts for co-author review.

Acknowledgements

If it takes a village to raise a child, I think it is fair to say that it takes an inspiring and supportive research team to guide a student in her pursuit of a Master of Science degree in Engineering. My thesis supervisors, the members of the BLINC Lab, the HAPTIX team, my family, and friends made up my research 'squad' – each of whom either pushed me to learn more, bombarded me with questions or ideas to test my learning, or supported my efforts to present the Gaze and Movement Assessment (GaMA) protocol in a manner that did justice to the hard work put into its creation.

First, I would like to thank my supervisors, Dr. Albert Vette and Dr. Jacqueline Hebert, for all of their support and guidance throughout my master's program. Jackie has been a mentor of mine since I first joined the BLINC Lab as a volunteer in the summer of 2014 and has helped to shape my enthusiasm for rehab research. Thank you for always making me feel like a valued member of your lab and for entrusting me with the validation testing of GaMA. I did not meet the other half of my supervision team until 2017 but had heard great things about Albert's research and teaching excellence. I was fortunate that he agreed to be my engineering supervisor, as his research passion was infectious, and he taught me how to develop the 'Vette-eagle-eye' attention to detail. In addition, I appreciate that Albert recommended me for a Mitacs-JSPS research opportunity. My summer of 2019 in Osaka, Japan proved to be a tremendous growth opportunity (and heaps of fun). Arigatō!

I would also like to thank the other members of the HAPTIX project, which spawned GaMA. I would like to thank Dr. Craig Chapman for his help with my sometimes-convoluted statistical analysis and Dr. Patrick Pilarski for helping with my data analysis (and always bringing enthusiasm to meetings!). Thank you to Aïda, Ewen, Quinn, and Riley for collectively contributing to the development GaMA, collecting the original non-disabled dataset, and helping me so much with replicating original data collection methods. Thank you to Ogi for spending so much time teaching me how to use the motion capture equipment and software, the eye tracking equipment, and how to run the experiments. Thank you to Mellissa for helping me with my data collection and for so many hours of motion capture data cleaning. Thank you to Tarvo, Brody, and Ogi for collecting and processing the simulated prosthesis data that I used. And finally, thank you to the

participants who volunteered their time so that I could collect research data (and for never whining, “are we done yet?”).

I would also like to thank my lab mates in the BLINC Lab for creating such an amazing work environment. I would especially like to thank Katherine, Rory, and Jon for welcoming this bright-eyed (and unskilled) Mechanical Engineering undergraduate and for introducing me to their world of research over the years. In addition, many thanks to all of my lab mates who allowed me to help out with their research – these opportunities have taught me so much.

I would also like to acknowledge the funding that made my research possible. Thank you to the Natural Sciences and Engineering Research Council of Canada, Alberta Innovates, the Faculty of Engineering, and the Faculty of Graduate Studies for their support. I am truly grateful.

Thank you to my awesome parents who endured my many ups and downs and who acted as great sounding boards. Thanks also to extended family members and friends who never faltered in their steadfast belief in me.

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Chapter 1. Introduction

1.1. Motivation

Upper limb sensory-motor impairments can hinder an individual's capacity to perform manual tasks. Interventions, including prostheses for individuals with upper limb amputation, are designed to restore lost function or to improve impaired function [1], so that activities of daily living (ADLs) can be accomplished independently. Numerous commercially available poly-articulated myoelectric hands exist today, which provide life-like grasp and release movements (such as the i-Limb, the BeBionic, and the Michelangelo) [1]. Despite the rapid evolution of upper limb prostheses, there is currently no one standardized measurement protocol in existence to assess the movement quality of device users. It is important to have a proven means by which to judge performance improvements introduced by novel prosthetic technology, especially since research evidence of enhanced function can guide medical decision-making, insurance provider coverage, and user expectations.

1.1.1. Using Measurement Technology to Quantify Upper Body Function

One approach to evaluating the effectiveness of hand and arm function is to use quantitative measurement technology. Three-dimensional optical motion capture has been shown to be beneficial in upper limb movement research [2], [3]. Eye tracking has been advantageous in studies that examine where and how attention is directed during activities that require hand-eye coordination [4], [5]. Eye tracking technology has already been integrated into motion capture systems for use in sports research to provide greater insight into visuomotor performance [6], [7]. When kinematic and eye-movement data are studied in combination, the means by which visual information guides motor planning, execution, and modification is better understood [8]. As such, the combined use of motion capture and eye tracking, in studies involving upper limb myoelectric prosthetic devices, can likewise be expected to offer a rich understanding of users' visuomotor behaviour. Assessments reliant on such specialized equipment, however, lack standardized protocols, can be criticized as not being generalizable to activities of daily function, and risk becoming obsolete as newer technologies emerge. Consequently, equipment-reliant assessments can hinder the opportunity for robust comparisons of outcome performance measures over time.

1.1.2. The Gaze and Movement Assessment (GaMA)

A collaborative group of researchers at the University of Alberta have developed the Gaze and Movement Assessment (GaMA) protocol [2]–[4]. GaMA addresses the need for standardized outcome performance measures that are representative of ADLs and achievable by individuals both with and without upper limb mobility restrictions [2]. GaMA was designed around two standardized functional tasks that incorporate common ADLs – picking up and transporting objects [2]. In addition to these tasks, GaMA also encompasses analysis software, which calls for a standardized data set of synchronized motion and eye data coordinates as input, and outputs measures of hand movement, angular joint kinematics, and eye gaze [2]–[4]. Researchers at the University of Alberta have begun to establish a repository of movement measures obtained using GaMA, including those from non-disabled participants (normative baseline) [2]–[4] and from non-disabled participants equipped with a simulated myoelectric device [9].

1.1.3. Using Simulated Myoelectric Prostheses as a Test Case for GaMA

A common technique used to study myoelectric prosthesis function is to outfit non-disabled research participants with simulated devices [10]–[14]. Doing so allows non-disabled individuals to act as substitutes for those with upper limb amputation. This technique is beneficial because the population of individuals with amputations that are suitable for device testing is small [15]–[18], and reduced sample sizes can hinder the potential for statistically valid findings. The non-disabled participant, in such research, activates a simulated myoelectric device using their forearm muscles, in the same manner as would an individual with an amputation wearing a custom-fitted prosthesis. However, it is not yet known if non-disabled individuals operate these devices using the same movement strategies as do those with upper limb amputation. This question presents an opportunity to use GaMA to quantify and compare the movement behaviour of myoelectric prosthesis users versus non-disabled users wearing a simulated prosthetic device.

1.1.4. Overarching Motivation

The overarching motivation of this thesis was to determine the validity of GaMA as a protocol for upper limb visuomotor behaviour measurement across research sites, by evaluating the reproducibility of its resulting movement measures. Testing the validity of measurement protocols is commonly done in gait and balance kinematics research [19]–[21], through assessments of repeatability and/or reproducibility. Repeatability judges the closeness of agreement between results obtained by a rater using the same methods, same participants, under the same circumstances [22], [23]. Thus far, the between-session repeatability of the hand movement and angular kinematic measures of GaMA has been confirmed [2], [3]. However, reproducibility of GaMA has not yet been assessed. Reproducibility judges the closeness of agreement between results obtained with the same methods, but under *different* conditions (such as different raters or experimental setups) [22], [23]. This thesis was motivated to assess the reproducibility of GaMA, so that it can be recognized as a valid upper limb visuomotor behaviour measurement protocol.

1.2. Research Objectives

The first objective of this thesis was to determine if GaMA is reproducible – that is, whether GaMA could be used to obtain the same hand movement, angular joint kinematic, and eye gaze measures when testing two independent groups of non-disabled participants, at different research sites equipped with different motion capture and eye tracking technology, and by different raters.

After confirming the reproducibility of GaMA, the second objective of this thesis was to apply GaMA to test the assumption that non-disabled individuals wearing a simulated prosthesis (a practice used in upper limb device research) and actual myoelectric prosthesis users exhibit comparable movement strategies. To accomplish this, an already established data set (collected at a research site using GaMA with participants wearing a simulated prosthesis) would be compared to data collected using GaMA at a new site using actual myoelectric prosthesis participants with transradial amputation.

If data collected using the GaMA protocol at different sites verifies that non-disabled individuals with a simulated prosthesis do act as movement behaviour proxies for actual prosthesis users, the continued use of simulated devices can be considered an acceptable practice in future upper limb research. Furthermore, this finding can become a catalyst for comparing inter-site data (collected using GaMA). Comparing such data would offer an important means of overcoming the burden of repeated data collection by research sites.

1.3. Thesis Structure

Chapter 2 of this thesis provides background information relevant to the understanding of the aforementioned objectives. Chapters 3 and 4 address this thesis' two research objectives – Chapter 3 presents the manuscript entitled "*Gaze and Movement Assessment (GaMA): Inter-site Validation of a Visuomotor Upper Limb Functional Protocol*" (submitted to *PLoS One*), and Chapter 4 presents the manuscript entitled *"Do the movement strategies of non-disabled individuals wearing a simulated prosthesis mimic those of myoelectric device users?"* (in preparation). Thereafter, Chapter 5 summarizes the major contributions of this thesis.

Chapter 2. Background

An understanding of the visuomotor demands required during ADL task performance, in both individuals with upper limb deficits and those without, can be made through analyses of hand trajectory, hand velocity, grip aperture, and angular joint kinematic measures [2], [3], along with analysis of visual attention allocation measures [4]. As a starting point for understanding such visuomotor measures, this thesis section first presents an overview of normative upper limb function. Next, it considers the implications of upper limb sensory-motor dysfunction, the role of rehabilitation therapy, and why therapy relies on functional assessments of patients. Introductions to optical motion capture and eye tracking technologies follow, as they provide means of collecting visuomotor data. Finally, GaMA is discussed in greater detail and a research application of GaMA is explained. Collectively, this section is intended to present the context necessary for the understanding of the methods and analyses undertaken by this thesis.

2.1. Normative Upper Limb Function

Upper limb function can be described as a linkage system, in which the end effector is the hand that interacts with an object, and together the wrist, elbow, and shoulder act to place the hand in space [24]. Trunk displacement can also be included in this sequence of movements, in instances where far-reaching is required. The hand can execute grip and pinch functions using its digits, and these functions can been measured by both speed and precision [25]. But given that the hand is part of a linkage system, it does not function in isolation. The wrist provides flexion or extension, and ulnar or radial deviation. The forearm allows supination or pronation. The elbow joint enables flexion or extension. The shoulder joint performs motions that include flexion or extension, abduction or adduction, and internal or external rotation. The shoulder also performs a vertical translation, which is not usually analyzed in kinematics research (nor in this thesis). Overall, an understanding of the upper limb linkage system helps researchers to anticipate how dysfunctions can impede movement control.

Although upper limb movements involved in ADLs are well-learned and take place with seemingly little attention, it has been shown that individuals performing such tasks unconsciously monitor every step of the process with their eyes [26]. It is this unconscious eye movement and visual focus that play important roles in an individual's planning and control of their upper limbs [26]. More specifically, it has been determined that vision guides the movements of the hand when reaching, grasping, and/or manipulating objects, [27]. Studies of eye and hand movements in food preparation tasks, for instance, have identified that the performers' eyes usually reach the next object in the sequence before any sign of manipulative action [28]. This finding indicates that eye movements are planned into upper limb motor patterns and that they lead each action; with each gaze fixation taking on the specific roles of locating, directing, guiding, and checking [28]. It is this interplay between eye gaze behaviour (movement and fixation) and limb movements that provide researchers with valuable information that is relevant to the understanding of upper limb movement strategies.

2.2. Upper Limb Amputation and Rehabilitation Considerations

An individual with an intact upper limb can repeatedly perform task-oriented movements such as picking up objects, opening jars, drinking from a cup, turning pages of a book, making phone calls, and so on. Motor control impairments, however, can impact reaching and grasping functions, including delayed movement times, complete loss of function, loss of ability to adapt to changing task demands, and slowed reaction times [29]. These types of dysfunction can be seen in stroke survivors [30], spinal cord injury patients [31], and as a result of upper limb amputations [32]. In the case of amputation, interventions, including prostheses, are designed to restore lost function or to improve impaired function, so that their users can accomplish ADLs independently [1]. Given that this thesis focuses on movement impairment due to upper limb amputation, the role of rehabilitation therapy aimed to train users in myoelectric prosthetic device control, along with the reliance on functional assessments to facilitate such therapy, are considered next.

Therapy after upper limb impairment, such as prosthesis fitting after amputation, is recommended to begin as early as possible and be intensive, repetitive, and task-oriented [29]. Rehabilitation programs are designed and delivered by rehabilitation therapists, who measure the baseline function of an individual prior to the introduction of a prosthetic device, as well as that individual's progress thereafter. Typical functional assessments involve hand-object interactions and appraise overall task achievement. They include tests such as the Box and Blocks Test [33], the Activities Measure for Upper Limb Amputees (AM-ULA) [34], the Assessment of Capacity of Myoelectric

Control (ACMC) [35], and the Action Research Arm Test (ARAT) [36], to name a few. Existing functional assessments provide a score to quantify upper limb function, but do not allow for precise quantitative evaluation of arm movement, hand movement, and grip adjustments [2], [3]. Furthermore, they do not provide an understanding of connections between specific body movements and corresponding visual attention. Recent studies of hand-eye coordination have recognized that both where and how visual attention is allocated during a manual task function is vital to assessing comprehensive movement kinematics [4], [5]. In fact, vision is said to play a dominant role in efficient object interaction [4], and eye gaze behaviour is recognized as an indicator of the strategies adopted by prosthesis users to compensate for the absence of sensory feedback [18]. Yet, there is no one standard procedure for the visuomotor assessment of upper limb movement. This lack of assessment methodology leads to incomplete measures of patient improvement for rehabilitation therapists, variability in therapy effectiveness, and no one standard method to compare interventions across practitioners and rehabilitation sites [37].

Valevicius et al. conducted a systematic review of twenty studies that used optical motion capture to obtain three-dimensional upper body kinematic measures of non-disabled individuals executing a variety of goal-oriented upper limb tasks [38]. No one upper limb data capture protocol was found to be superior in all factors under consideration (including the types and characteristics of the tasks performed, the characteristics of the motion capture marker set used, the kinematic measures obtained, and the validity and reliability of the protocols reported [38]). Of particular concern was that most studies did not assess trunk kinematics, so could not adequately characterize the compensatory movements in populations with impairments [38]. Monitoring of upper body compensatory patterns is believed to be critical for improving functional outcomes during rehabilitation [39]. Valevicius et al. recommend that, for future studies employing motion capture technology, a standardized upper body kinematic model that shows high validity and reliability in non-disabled individuals be established, after which it can be used in populations with upper limb impairment [38].

Given Valevicius et al.'s recommendation for a standardized upper body kinematic assessment model and protocol [38], and recognizing that eye gaze behaviour (or visual attention) is an indicator of upper limb movement strategies used for hand-eye coordination [4], [5], [18], [28], a standardized visuomotor assessment protocol that provides comprehensive measurement data for analyses, would be of benefit to both rehabilitation researchers and practitioners. As three-dimensional optical motion capture is known to effectively collect data about reaching, grasping and manipulation of an object, and eye tracking is known to collect data about eye gaze behaviour, a closer look at these technologies is presented next. Thereafter, details explaining how GaMA can be used to synchronously collect and combine visuomotor data to yield rich upper body hand movement, angular joint kinematic, and eye gaze measures will be provided.

2.3. Three-Dimensional Optical Motion Capture Technology

Three-Dimensional (3D) optical motion capture technology can be used to track human movement and to obtain data relevant to kinematic analysis. The increased demand for motion capture options, in both the biomechanics and animation fields, has ushered in a new generation of low-cost motion capture hardware and software systems (compared to high-end solutions used in the film industry and large research institutions) [40]. These low-cost systems have been found to be comparable in accuracy to their high-end counterparts, thereby providing research laboratories with limited budgets access to tools that enable kinematic analysis [40]. Given that the demand for motion capture is on the rise, with newer hardware and software rapidly emerging (such as markerless motion capture) this thesis does not aim to discuss specific technologies. Instead, it intends to give readers an overview of the 3D optical motion capture process, as used in kinematics research conducted in academic research laboratories.

3D optical motion capture systems use cameras to track markers affixed to movement points of interest, along with computer software for data collection and manipulation. There are two specific types of motion capture markers used by such systems: passive and active markers [38]. Passive markers are small spheres covered in a retroreflective material so that they can reflect light, whereas active markers are small diodes that emit infrared light [41]. Despite being more robust, active markers require additional cables and batteries, thereby limiting a wearer's freedom of movement [42]. Given this limitation, only information about the 3D optical motion capture process that employs passive markers is discussed in this thesis.

Marker Placement: Marker placement is determined by the movement analysis requirements of a kinematic study. Two common types of marker placement models used in kinematics research are anatomical and cluster models [38]. Anatomical models involve the placement of individual motion capture markers on a research participants' bony landmarks (where soft tissue covers a bony protrusion) [38]. Common errors that occur when using this model stem from inaccurate placement of markers on such landmarks [43], from movement of soft tissue over them [44], and from marker occlusion [45]. To minimize marker occlusion errors, clusters of markers can be mounted onto a rigid surface plate, with each plate affixed to a different body segment [45]. This cluster model approach requires that joint centres be identified at anatomical landmarks, either through digitization or by affixing individual markers at these locations [45]. Joint centres are tracked during a calibration process (necessary for joint angle calculations), whereas only the clusters are tracked during data collection [45]. Alternatively, a "Clusters Only" model can be used, which notably does not reference anatomical landmarks and instead captures the orientation of marker clusters at known joint angles (obtained during a calibration pose process) [45]. Marker cluster orientation information is subsequently used to calculate joint angles [45]. For comparative purposes, Figure 2-1 [45] shows an upper body anatomical marker model, a "Clusters Only" model, and a cluster model with anatomical markers.

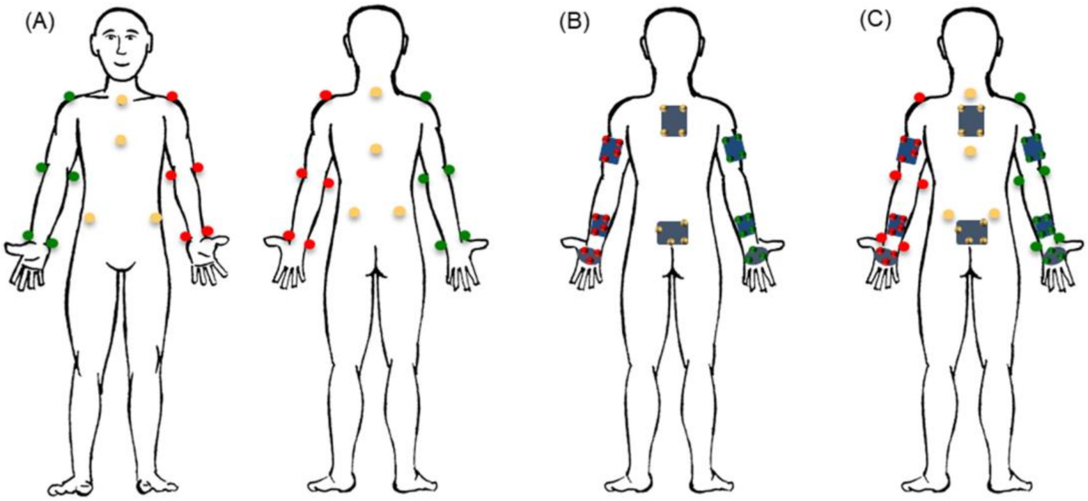

Figure 2-1: An anatomical model (A), a "Clusters Only" model (B), and a cluster model with anatomical markers (C) [45].

Cluster models (with digitization or anatomical markers) are known to reduce the incidence of model error by minimizing the effect of marker occlusion, but a Clusters Only model extends this benefit by eliminating the requirement for precise landmark identification [45]. As such, most errors introduced by a Clusters Only model are offsets in joint angles [45].

Camera Configuration: In passive marker systems, cameras track retro-reflective markers that are precisely affixed to physical locations. These cameras emit infrared frequencies (not visible to the human eye) that reflect off of the markers. When two or more cameras see a marker reflection, the position of that marker in 3D space can be computed via triangulation (by a computer equipped with accompanying software) [46]. So, to avoid marker data loss, motion capture cameras must be positioned such that all markers can be seen by at least two cameras at all times during motion capture. Figure 2-2 [47] further explains this requirement of 3D marker triangulation.

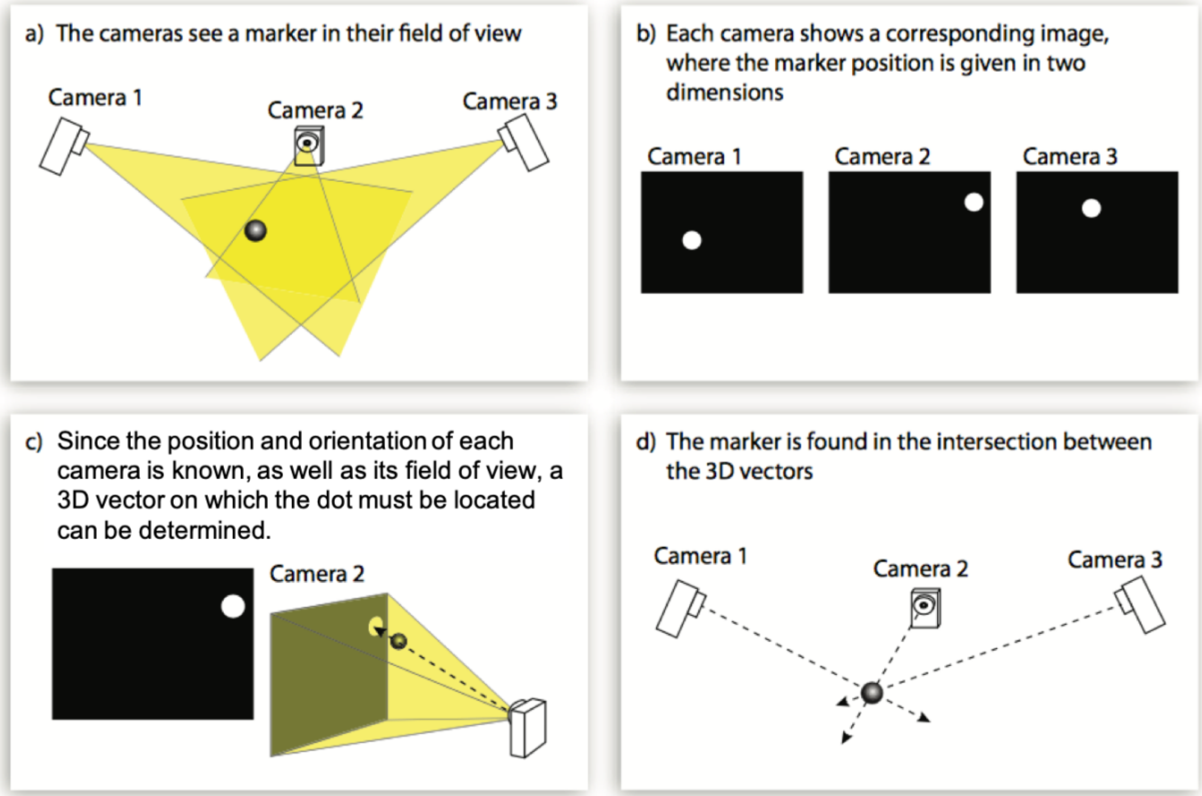

Figure 2-2: Cameras and 3D marker position calculations [47].

It is important, therefore, that a research participant's anticipated movements be taken into consideration during the camera configuration process. A resulting research study capture area equipped with cameras might look like that depicted in Figure 2-3 [48].

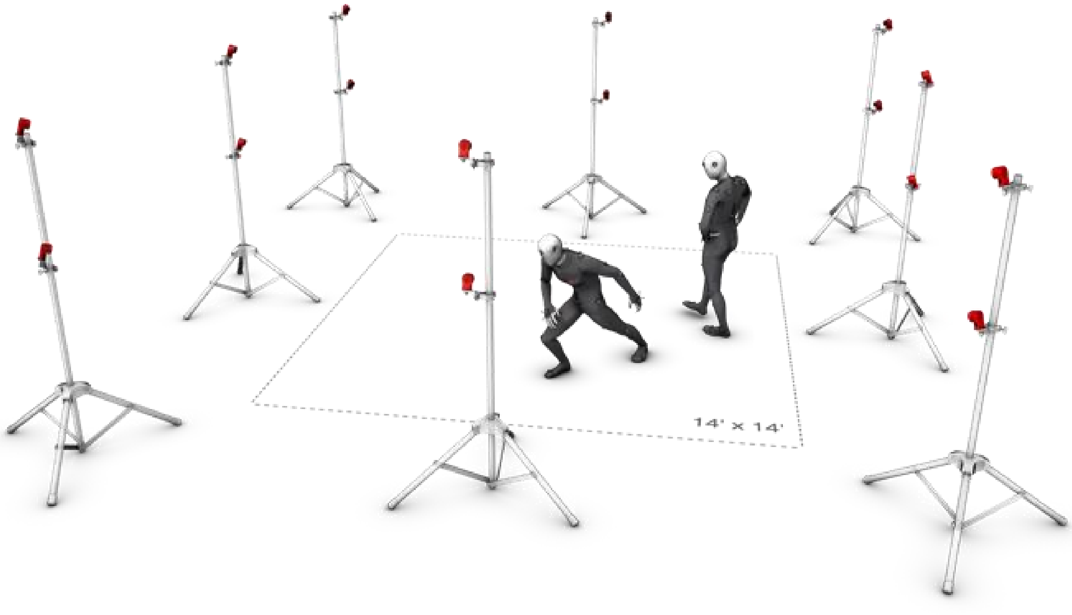

Figure 2-3: Example capture area with OptiTrack cameras [48].

Camera Calibration: Calibration is notably the most important step in 3D optical motion capture system setup [49]. Camera calibration allows the system software to calculate the relative location and orientation of all cameras in a capture area. Since each camera in an area can only see the two-dimensional position of each marker within the camera's field of view, the position of each camera with respect to the others must be known by the software. With this information, the 3D position of markers can be calculated [49]. One method of camera calibration involves moving a wand around the capture area [47]. The data from this 'wanding' process is used to calculate the position of each camera [50]. Thereafter, a calibration frame is placed on the ground to define the global origin and coordinate axes of the motion capture area [49].

Data Collection: Following motion capture system setup, a research specific kinematic calibration may be undertaken. A kinematic calibration facilitates the virtual prediction of the anatomical landmarks and joint centres of a participant (either in real-time or in post-processing), and is necessary for calculating joint angles [45]. Once kinematic calibration is complete, data collection trials can begin. During these trials, it is important for the rater to ensure that marker attachments do not move or get repositioned. It is the marker position data that is systematically captured by the system software (set to study-specified capture rates). Figure 2-4 [51] shows an example of a participant in a capture area and the on-screen representation of that participant as captured by multiple cameras.

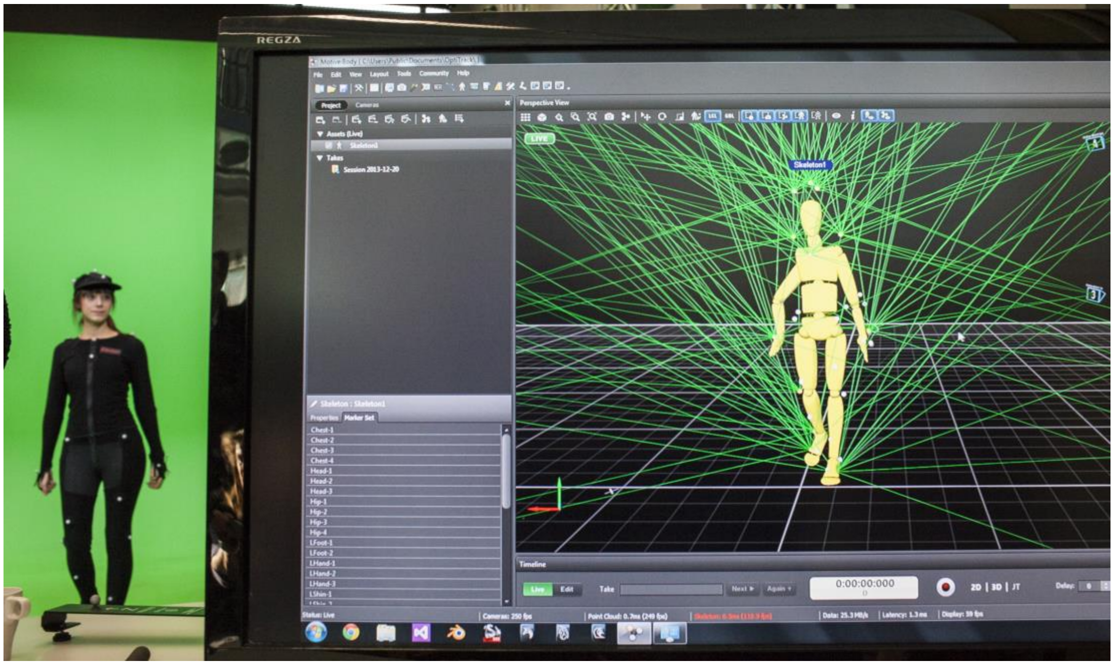

Figure 2-4: Example live capture area and on-screen representation [51].

Post Processing: Following data collection, raters can use 3D optical motion capture system software to identify erroneous data [52]. This software includes proximity routines that can be used to reconstruct 3D data. Even so, the rater should examine the data (before and after using such software solutions) to identify any unusual outcomes. Optical motion capture software also provides tools to ‘clean’ data, guided by the decision making of the rater. The main issues that tend to appear in raw motion capture data include gaps in marker data, errors in marker labelling, and noise [52]. Gaps in the data are introduced when camera views are occluded. They can be filled by interpolating between two data points (provided that the gaps are not too large) or by extrapolation at the endpoints of a recording [47]. As passive markers of the same size can appear to be identical to motion capture software, marker labelling errors can easily occur [53]. Mislabelled markers are usually manually relabelled by a rater, although algorithms have been developed to automate this process [53]. Finally, noisy (but otherwise accurate) motion capture data can be smoothed using a lowpass filter routine.

Calculations of Measures: After 3D optical motion capture data are cleaned and processed, kinematic calculations can take place. These calculations can yield linear measures of specific body parts, angular measures at joints, or a combination of such measures to quantify the body movements of interest [54].

2.3.1. Differences Between 3D Optical Motion Capture Systems

3D optical motion capture systems, used in kinematics research and rehabilitative clinical practice, offer different hardware and software solutions. Generally, hardware solution differences depend on camera capabilities and the number of such cameras required [55]. Some lower cost cameras have limited strobe strength that yield relatively small capture volumes [55]. So, although an individual camera cost may be lower, more cameras may be required to cover a given capture area. The software that controls the system hardware also differs amongst motion capture solutions. Some software provides built-in toolboxes for data visualization and animation [55]. More comprehensive (and expensive) software provides increased options for data management such as variable data streaming frequencies, numerous calibration algorithms, numerous reconstruction algorithms, and data export formats for post-processing of the data [55]. But, depending on the nature of a study, a low-cost motion capture system may provide sufficiently accurate data for kinematics research [40]. Ultimately, it is the goal and budget of a research project that dictate what 3D optical motion capture system will suffice.

2.4. Eye Tracking Technology

When humans look at visual targets, both a fixation and gaze shift take place [56]. A fixation is the maintenance of a gaze at a target, whereas gaze shifts relate to eye movements [56]. Eye fixations and gaze shifts can be measured using eye trackers. Both head-mounted and desktop-mounted devices can be used to track a participant's eye movements. Desktop-mounted devices require that a participant's head remains stationary during tracking [57]. Head-mounted devices do not have this restriction and are more favourable in studies where a participant's head is prone to movement, as in kinematics research. These wearable eye trackers allow researchers to record gaze behavior as participants move around in an environment and interact with real-world objects therein [58]. It is for this reason that only head-mounted eye trackers are presented in this thesis.

As an example of this technology, the Tobii Pro head-mounted eye tracker is equipped with cameras, illuminators, and controller software, as depicted in Figure 2-5 [59].

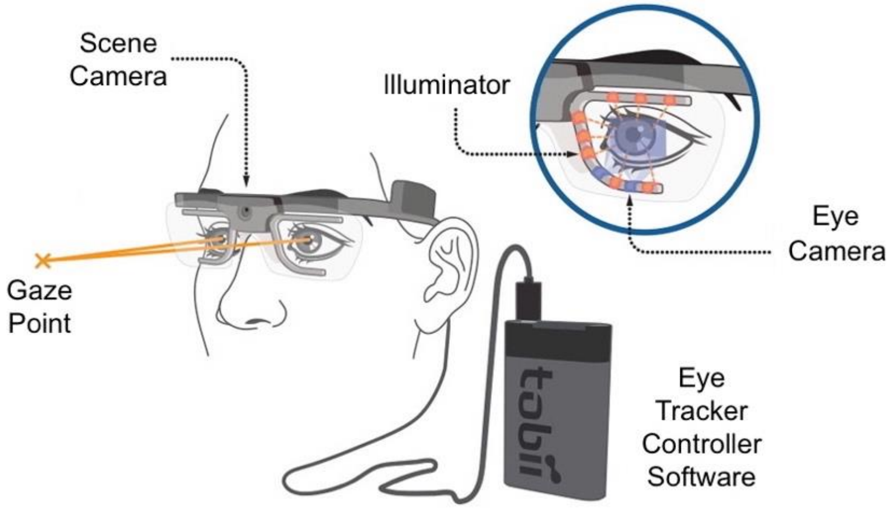

Figure 2-5: Example Tobii Pro head-mounted eye tracker [59].

Other commercial eye trackers include the Ergoneers Dikablis, SMI Eye Tracking Glasses, and the ISCAN OmniView [56], as well as eye trackers with open-source software like Pupil [60]. The Tobii Pro system, depicted in Figure 2-5 [59], is equipped with two types of cameras (a scene camera and eye cameras), which are attached to a pair of eyeglass frames. The scene camera records what the wearer is looking at, whereas the eye cameras record the position of the wearer's eyes. Illuminators emit near-infrared light patterns (undetectable by the human eye) onto the eyes, as image processing software recognizes details in the wearer's eye positions and reflection patterns. Based on these details, a software algorithm calculates the eyes' position and gaze point. Gaze points are expressed as two-dimensional locations and lack reference to any external features of the environment in which they were captured [58]. Eye tracking software can be used to map these gaze points to scene camera coordinates.

System Setup: Eye tracker setup requires that the tracker frames fit securely on a participant's head. To ensure that eye positions are tracked as accurately as possible, some head-mounted eye trackers allow the positioning of the eye cameras to be adjusted [56]. The scene camera of the head-mounted eye tracker can also be adjusted by the rater to ensure that the environmental view of interest is captured as a participant moves.

Calibration Process: The calibration process estimates the geometric characteristics of a participant's eyes (location of the centre of the pupil, the border between the iris and the white of the eye) and uses these measures as the basis for gaze point calculations [61]. This process takes place before eye tracking data recording begins. A typical calibration procedure presents a participant with a set of visual targets to look at (unique to each eye tracker system and/or study) while measurements are systematically taken to capture the characteristics of that participant's eyes and/or the reflection of light off their cornea [61]. During this process, positions of a participant's eyes are collected and analyzed by the eye tracker software, and optionally displayed on-screen for scrutiny by the rater. The resulting calibration information is then integrated (mapped) by the eye tracker control software for the calculation of gaze points during the recording of data.

Data Collection: After calibration, data collection can begin. During the data collection process, it is important for the rater to ensure that the eye tracker frame and cameras are not repositioned by a participant.

Post-Processing: Errors can be removed from eye tracking data after they have been recorded. Errors are commonly introduced by a participant's blinks and may result in momentarily incorrect data or in a data gap [62]. Other causes of eye tracking errors are eyelashes occluding the eye, eye makeup being tracked instead of the dark pupil, reflection off of glasses or contact lenses, or poor illumination of the eye [63]. Corrections of such eye tracking errors can either be done manually by a rater using the eye tracking software, or correction scripts can be developed to automate this process. High-frequency noise can also exist in eye tracking data and should be removed by filtering.

Calculations of Measurements: With calibration information mapped by the eye tracker, and after eye position data is collected and post-processed, calculations can be performed to identify and quantify behaviours such as fixations and gaze shifts. Furthermore, these calculations can identify areas of interest, to which fixations repeatedly land.

2.4.1. Differences Between Head-Mounted Eye Tracking Systems

Head-mounted eye tracking systems offer the opportunity for participants to navigate freely in an environment. The hardware in these systems include a head-mounted eye glass frame, cameras, and illuminators. Most commercial, full-featured, head-mounted eye trackers reportedly are considered to be expensive [56], [64], with binocular eye trackers more so than their monocular counterparts [65]. However, these high prices can be mainly attributed to advances in eye tracking system software, as well as to the added cost of offering customer support [66]. As such, systems with more advanced software remain costly. Consequently, researchers are turning to open source eye tracker software, as well as to devices that support such lower cost software solutions [58], [60], [66].

2.5. The Gaze and Movement Assessment (GaMA) in Detail

GaMA addresses the need for standardized outcome measures that involve tasks that are representative of ADLs, amenable to both motion capture and eye tracking, and are achievable by individuals with and without upper limb mobility restrictions [2]. GaMA was designed around two standardized functional upper limb tasks, known as the “Pasta Box Transfer Task” and the “Cup Transfer Task” [2]. It also includes analysis software that requires synchronized motion and eye data coordinates as input, and outputs hand movement, angular joint kinematics, and eye gaze measures [2]–[4]. GaMA’s two functional tasks were designed to be challenging, but not impossible, for clinical populations to perform [2]. They were also designed to include distinct movements that could easily be segmented into Reach, Grasp, Transport, and Release phases, for detailed visuomotor analysis.

The Pasta Box Transfer Task: The Pasta Box Transfer Task requires a research participant to move a pasta box (specifically, a 225g box of Kraft Dinner Original) between a counter to their right and shelves at different heights in front of them – a task that mimics reaching for a kitchen item and moving it to a counter or shelf. This task involves the grasp of a deformable object (pasta box) and requires a participant to move it across their body’s midline.

The Cup Transfer Task: The Cup Transfer Task introduces greater risk by using cups filled with beads (specifically, 5oz Dixie® Wax Treated Paper Cold Cups filled with soft plastic pellets), and requires a participant to carefully navigate the cup over a barrier before setting it down – a task that mimics moving filled, open containers around a sink or countertop using different grasp patterns. So, this task involves the grasp of a deformable object (cup that risks content spillage) and requires a participant to move it across their body’s midline.

GaMA uses 3D optical motion capture and eye tracking technologies to capture movement and eye data as research participants execute these tasks. More specifically, it uses a Clusters Only kinematic model to obtain the movement data [45], as this model readily facilitates both upper body angular kinematic analysis and hand function analysis (when paired with individual markers placed on the index finger and thumb) [2], [3]. Furthermore, GaMA also includes methods to simultaneously capture eye data during task execution [4]. This data allows assessment of the visual demands required of each functional task [4]. So collectively, GaMA includes:

(1) a methodology for a rater to administer two standardized functional tasks;
(2) a methodology to use motion capture and eye tracking hardware and software solutions to obtain synchronized movement and eye data during functional task execution; and
(3) analysis software, which calls for a standardized data set of synchronized motion and eye data coordinates as input, and outputs measures of hand movement, angular joint kinematics, and eye gaze.

2.6. A Research Application of GaMA

With the reproducibility of GaMA established, this assessment protocol could facilitate comparisons of outcome measures across sites, thereby making a much larger pool of data accessible to researchers seeking to answer relevant clinical questions. Already GaMA has been used to successfully measure the visuomotor behaviour of prosthesis users at a research site [67]. Combining this data with that of another site would offer an important means of overcoming the traditional limitations of small sample sizes of research participants – that is, of individuals with upper limb amputation who use a myoelectric prosthesis. Furthermore, adoption of GaMA across sites would facilitate the creation of a shared upper limb visuomotor data repository. Such a repository could make accrual of larger sample sizes of participants less of a challenge to researchers, and comparisons of measures between sites possible.

One application of an inter-site comparison using GaMA would be to study an outstanding question in prosthetic literature: Do non-disabled individuals operating a simulated myoelectric prosthesis use the same movement strategies as those with transradial upper limb amputation? It is well known that one obstacle to upper limb prosthetic research is that it can be difficult to recruit suitable numbers of individuals with amputation [68]. A low number of appropriate research participants reduces sample sizes and hinders the potential for statistically significant findings. To combat this research problem, a common technique used to study myoelectric prosthesis function is to outfit non-disabled research participants with a simulated device. Doing so allows these individuals to act as substitutes for those with upper limb amputation. The non-disabled users operate a simulated prosthetic device by activating their forearm muscles – in a similar manner as would an individual with an amputation using a custom-fitted prosthesis. Simulated prostheses have been used to investigate different control strategies [11], [12], [69]–[73], the effect of sensory feedback [13], [74]–[76], how individuals learn to control myoelectric prostheses [77]–[79], different prosthesis designs [80]–[82], compensatory movements [83], [84], and hand-eye coordination [5], [85]. Despite such frequent use of simulated prostheses, it has yet to be determined if non-disabled individuals operate myoelectric devices using comparable movement strategies as those with upper limb amputation. The second objective of this thesis addresses this very question, and also serves to demonstrate the value of using GaMA. That is, that a standardized assessment protocol can facilitate a comparative analysis of data sets originating from upper limb research at different sites.

The following two chapters focus on the objectives of this thesis: to assess the reproducibility of GaMA, and an application of GaMA that demonstrates the benefit of using this protocol for inter-site data comparison.

Chapter 3. Inter-Site Validation of GaMA

The material presented in this chapter is currently under review for publication as the article:

H.E. Williams, C.S. Chapman, P.M. Pilarski, A.H. Vette, J.S. Hebert, "Gaze and Movement Assessment (GaMA): Inter-site Validation of a Visuomotor Upper Limb Functional Protocol," submitted to PLoS One.

The contents of this chapter are identical to the material presented in the submitted manuscript, with the exception of supplementary figures and tables moved into the body of the chapter and text formatting.

3.1. Abstract

Background: Successful hand-object interactions require precise hand-eye coordination with continual movement adjustments. Quantitative measurement of this visuomotor behaviour could provide valuable insight into upper limb impairments. The Gaze and Movement Assessment (GaMA) was developed to provide procedures for simultaneous motion capture and eye tracking during the administration of two functional tasks, along with data analyses methods to generate standard outcome metrics of visuomotor behaviour. The objective of this study was to investigate the reproducibility of the GaMA protocol across two independent groups of non-disabled participants, with different raters using different motion capture and eye tracking technology.

Methods: Twenty non-disabled adults performed the Pasta Box Transfer Task and the Cup Transfer Task. Upper body and eye movements were recorded using motion capture and eye tracking. Measures of hand movement, angular joint kinematics, and eye gaze were compared to those from twenty non-disabled adults who had previously performed the same protocol at a different site.

Results: Participants took longer to perform the tasks versus those from the earlier study, although the relative time of each movement phase was similar. Measures that were dissimilar between the groups included hand distances travelled, hand trajectories, number of movement units, eye latencies, and peak angular velocities. Similarities included all hand velocity and grip aperture measures, eye fixations, and most peak joint angle and range of motion measures.

Discussion: The reproducibility of GaMA was confirmed by this study, despite a few differences introduced by learning effects, task demonstration variation, and limitations of the kinematic model. The findings from this study provide confidence in the reliability of normative results obtained by GaMA, indicating that it accurately quantifies the typical behaviours of a non-disabled population. This work advances the consideration for use of GaMA in populations with upper limb sensorimotor impairment.

3.2. Introduction

Sensory-motor impairments including stroke [30], amputation [32], and spinal cord injury [31] can lead to deficits in upper limb performance and hamper activities of daily living that require precise hand-object interactions [29]. Various functional assessments are used to gauge the impact of upper limb impairment and to monitor rehabilitative progress thereafter [86], [87]. However, such assessments often do not precisely quantify hand and joint movements, grip adjustments [2], [3], nor hand-eye interaction, which is recognized as an important behaviour during grasp control [4], [56]. Quantitative measurement of visuomotor behaviour collected during the execution of functional tasks can enhance the understanding of these movement features. Measurement technologies commonly used for this purpose include eye tracking and motion capture. Assessments reliant on such specialized equipment, however, suffer from a lack of standardized protocols and can be criticized as not being generalizable to activities of daily function. Furthermore, technology-based assessments risk becoming obsolete as newer technologies emerge and hinder the opportunity for robust comparisons of outcomes over time.

The GaMA protocol was designed to overcome these limitations. GaMA includes two standardized functional upper limb tasks that incorporate common dextrous hand demands of daily living [2]. GaMA also encompasses analysis software, which calls for a standardized data set of synchronized motion and eye data coordinates as input (obtained using motion capture and eye tracking during functional task execution) and outputs measures of hand movement, angular joint kinematics, and eye gaze [2]–[4]. GaMA’s input data set can be created by various data collection hardware and software solutions, rendering the assessment protocol amenable to technological evolution (for example, markerless motion capture and the development of less intrusive eye trackers). Additionally, GaMA measures remain relevant and equipment-independent for future comparative purposes, potentially both within and across research sites. The ability to compare results across sites would be extremely valuable as it could facilitate larger subgroup comparisons when smaller populations of individuals with upper limb impairments are studied, such as upper limb prosthesis users.

In order to validate a new protocol such as GaMA, it is essential to first determine reproducibility. Reproducibility of a test or method is defined as the closeness of the agreement between independent results obtained by following the same procedures, but under different experimental conditions [22]. Due to the inherent variability found in clinical populations, reproducibility of a test to assess movement behaviour is typically first studied in a non-disabled population. While intra-rater test-retest reliability of GaMA has been demonstrated for hand movement and angular joint kinematic results for non-disabled individuals [2], [3], it has yet to be determined whether these and other measures obtainable by GaMA are reproducible across raters and sites. Furthermore, it is often assumed that the non-disabled population will behave similarly (or identically) across test sites; yet, it is known that deviations from protocols can result in data set disparity amongst the population [88]. If a standardized protocol can be shown to yield measures that are similar across sites, the data sets could be combined for a richer understanding (or more saturated data set) of non-disabled movement behaviour.

The objective of this study, therefore, was to conduct an inter-site validation of GaMA by assessing the reproducibility of the visuomotor measures in non-disabled individuals presented by Valevicius et al. and Lavoie et al. [2]–[4]. More specifically, this study sought to determine whether the same hand movement, angular joint kinematic, and eye gaze measures could be obtained using GaMA, by testing two independent groups of non-disabled participants, at different research sites equipped with comparable motion capture and eye tracking technology, and by different raters. Establishing the reproducibility of GaMA in the non-disabled population will advance its consideration as an outcome assessment protocol for populations with sensory-motor impairments of the upper limb.

3.3. Methods

For comparative purposes, the research conducted by Valevicius et al. [2], [3] and Lavoie et al. [4] is referred to in this paper as ‘the original study’, and the data set analyzed by these studies is referred to as ‘the original data set’. The new research presented in this paper is referred to as ‘the repeated study’ and its data as ‘the repeated data set’. Unless otherwise specified, the same procedures were followed in both studies. Ethical approval for these procedures was obtained by the University of Alberta Health Research Ethics Board (Pro00054011), the Department of the Navy Human Research Protection Program, and the SSC-Pacific Human Research Protection Office.

3.3.1. Participants

A total of 22 non-disabled adults were recruited to participate in the repeated study. Data from two participants were removed due to problems arising from software issues. The characteristics of the 20 participants from the original study [2]–[4] and the 20 participants in the repeated study are detailed in Table 3-1. In both studies, two participants performed the tasks without corrected vision, since they had to remove their glasses to don the eye tracker. These participants, however, reported that their vision was sufficient to allow them to confidently perform the task.

Table 3-1: Original and repeated study participant characteristics.

Research Participant Characteristics	Original Study	Repeated Study
Male Participants	11	13
Female Participants	9	7
Self-Reported Right-Handed Participants	18	19
Participants with Normal or Corrected to Normal Vision	18	18
Participant Age (years – mean ± standard deviation)	25.8 ± 7.2	24.4 ± 7.3
Participant Height (cm – mean ± standard deviation)	173.8 ± 8.3	171.0 ± 7.7

3.3.2. Equipment

Motion capture and eye tracking hardware and software specifications for the original study and the repeated study are indicated in Table 3-2. The equipment was set up in the repeated study as specified in the original study [2]–[4]. Rigid plates and a headband (each holding four retroreflective markers) were attached to the participants in accordance with Boser et al.’s *Clusters Only* kinematic model [45]. To improve rigid body motion tracking in the repeated study, the hand plates were redesigned as shown in Figure 3-1. For both studies, markers were attached to the index finger (middle phalange) and thumb (distal phalange) [2]; a head-mounted eye tracker was placed on the participant and positioned in accordance with each manufacturer's instructions; and a motion capture calibration pose was collected for each participant, as outlined by Boser et al. [45].

Table 3-2: Specifications of the motion capture and eye tracking systems used in the original and repeated studies. For motion capture, the camera type, number of cameras, and the sampling frequency are included. For the head-mounted binocular eye trackers, the headset model and eye camera sampling frequency are listed.

Specifications	Original Study	Repeated Study
Motion Capture Camera	Vicon Bonita 10 (Vicon Motion Systems Ltd, Oxford, UK)	OptiTrack Flex 13 (Natural Point, OR, USA)
Number of Cameras	12	8
Camera Sampling Frequency	120 Hz	120 Hz
Head-mounted Binocular Eye Tracker	Dikablis Professional 2 (Ergoneers GmbH, Manching, Germany)	Pupil (Pupil Labs GmbH, Berlin, Germany)
Eye Camera Sampling Frequency	60 Hz	120 Hz

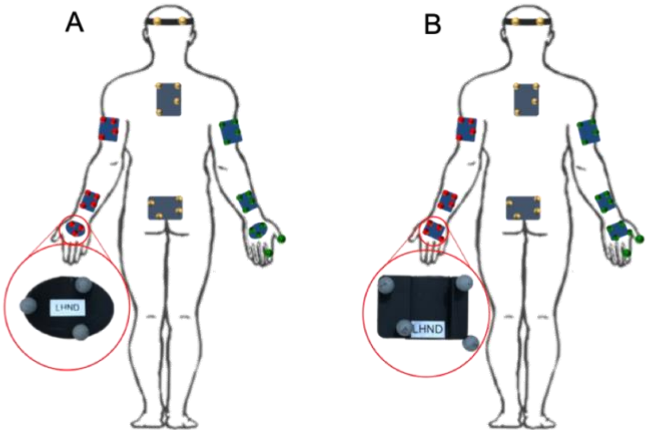

Figure 3-1: Retroreflective marker placement on participants in the original study (A) and repeated study (B), including differences in the hand marker plate designs.

3.3.3. Data Collection

In both studies, the two functional tasks introduced by Valevicius et al. (the Pasta Box Transfer Task and Cup Transfer Task) [2] were administered. Each participant completed 20 error-free trials of the two tasks, while simultaneous motion and eye tracking data were collected. Prior to this, each participant was given verbal instructions, a demonstration, and at least one familiarization trial of each functional task. Task order was randomized for each participant in the repeated study. At least two gaze calibrations (outlined by Lavoie et al. [4]) were collected before participants executed their initial trial of each task, and one after they completed their final trial of the last task; given that there were two functional tasks, a minimum of 5 calibrations were done per participant.

The original data collection protocol differed from the repeated study in one notable way. In the original study, every participant performed a total of 60 trials of each task, 20 of which were under each of the following conditions: (1) only motion capture data were collected, (2) only eye tracking data were collected, and (3) both motion capture and eye tracking data were collected. As the repeated study consisted solely of collecting data during simultaneous motion capture and eye tracking, it was only compared to that of the original data set captured under condition (3) – 'both'. In the original study, the order of conditions for each participant was block randomized. As a consequence of the randomization order, three quarters of the original study participants were afforded at least 20 extra trials executing each functional task prior to testing under the 'both' condition.

3.3.4. Experimental Data Analysis

Data analysis in the repeated study was undertaken as outlined by Valevicius et al. and Lavoie et al. [2]–[4]: motion capture marker trajectory data and pupil position data were filtered and synchronized; hand movement and angular kinematic measures were calculated; the virtual location of the participant's gaze (represented by a gaze vector) was determined using gaze calibration data; and gaze fixations to areas of interest were calculated. Due to insufficient pupil data, the data from one participant were removed from the repeated data set for the Cup Transfer Task, and data from four participants were removed for the Pasta Box Transfer Task.

For each functional task, the repeated data set were divided into distinct *movements* based on hand velocity, the velocity of the task object(s), and grip aperture values, as per Valevicius et al. [2]. The data from each movement were further segmented into the *phases* of 'Reach', 'Grasp', 'Transport', 'Release', and 'Home'; the Home phase was not used for data analysis. Due to the short duration of the Grasp and Release phases, combined *movement segments* of 'Reach-Grasp' and 'Transport-Release' were used in hand movement analysis [2]. Eye latency measures were calculated at instances of *phase transition*, both at the end of a Grasp phase and at the Beginning of a Release phase (referred to as 'Pick-up' and 'Drop-off' by Lavoie et al. [4]). An illustration of how one distinct movement can be broken into the above-mentioned subsets (phases, movement segments, and phase transitions) can be found in Figure 3-2.

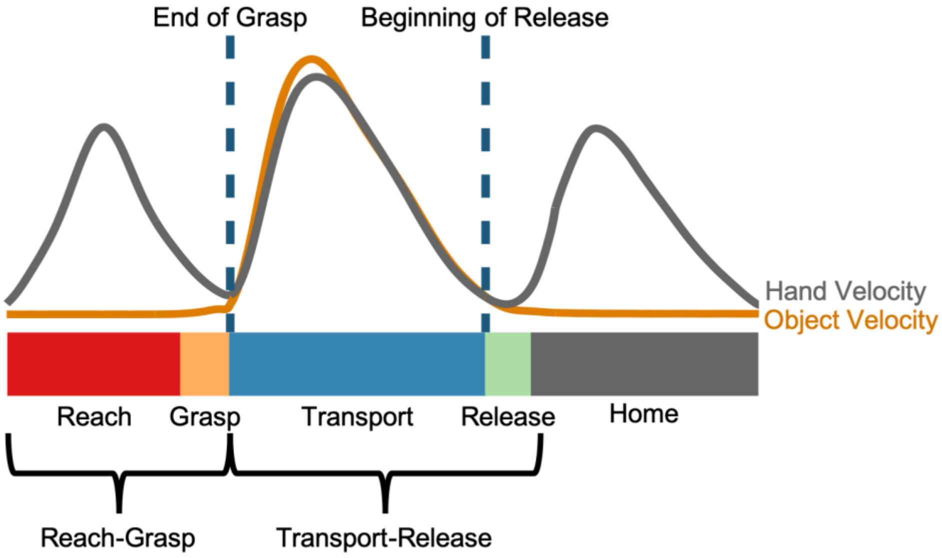

Figure 3-2: Phase transitions, phases, and movement segments within one movement, including the hand and object velocity profiles that would occur within the movement.

3.3.5. GaMA Measures

Duration (phase and trial), hand movement, angular joint kinematic, and eye gaze measures were calculated for the original and repeated studies, as outlined by Valevicius et al. [2], [3] and Lavoie et al. [4], and are listed in Table 3-3. Lavoie et al.'s 'fixations to future' measure was not considered in this study as these fixations were shown to be unlikely to occur in non-disabled participants (for both tasks) [4]. In addition to the measures listed in Table 3-3, the relative duration of each phase was calculated as the percent of time spent in that phase, relative to the given Reach-Grasp-Transport-Release sequence.

Table 3-3: Comparative measures, including duration, hand movement, angular joint kinematic, and eye gaze measures, and the subsets of each movement for which they were calculated.

Type of Measure	Measures	Movement Subsets
Duration (from Lavoie et al. [4])	Phase duration	Reach, Grasp, Transport, Release
Hand Movement (from Valevicius et al. [2])	Hand distance travelled Hand trajectory variability Peak hand velocity Percent-to-peak hand velocity Number of movement units	Reach-Grasp, Transport-Release
	Peak grip aperture Percent-to-peak grip aperture Percent-to-peak hand deceleration	Reach-Grasp
	Percent fixation to Hand in Flight Number of fixations to Hand in Flight	Reach, Transport
	Eye Arrival Latency Eye Leaving Latency	End of Grasp, Beginning of Release
Angular Joint Kinematics (from Valevicius et al. [3])	Peak angle, range of motion, and peak angular velocity for the following degrees of freedom: - Trunk flexion/extension - Trunk lateral bending - Trunk axial rotation - Shoulder flexion/extension - Shoulder abduction/adduction - Shoulder internal/external rotation - Elbow flexion/extension - Forearm pronation/supination - Wrist flexion/extension - Wrist ulnar/radial deviation	Movement only
Eye Gaze (from Lavoie et al. [4])	Percent fixation to Current Number of fixations to Current	Reach, Grasp, Transport, Release

In the repeated study, the calculation of hand movement measures was altered due to the creation of a virtual rectangular prism, which approximated the participant's hand position at each point in time. Using the centre of this prism, hand position and velocity were subsequently calculated. For comparative purposes, the original study's hand movement results were recalculated using this methodology (rather than the original calculation of Valevicius et al. using the average position of the three hand plate markers [2]).

3.3.6. Statistical Analysis

The goal of the statistical analysis was to detect significant differences between the original and repeated data sets, and to determine whether such differences were more pronounced for particular movements and/or movement subsets (phase, movement segment, or phase transition). To investigate differences between the two groups of participants, a series of repeated-measures analyses of variance (RMANOVAs) and pairwise comparisons were conducted for each measure and task. RMANOVA group effects or interactions involving group were followed up with either an additional RMANOVA or pairwise comparisons between groups if the Greenhouse-Geisser corrected *p* value was less than 0.05. Pairwise comparisons were considered to be significant if the Bonferroni corrected *p* value was less than 0.05. Detailed statistical analysis methods can be found in Appendix A.

3.4. Results

3.4.1. Duration

For both the Pasta Box Transfer Task (or 'Pasta') and the Cup Transfer Task (or 'Cups'), the repeated study participants took significantly more time to complete the tasks than the original study participants (Pasta: 11.8 ± 3.4 seconds versus 8.8 ± 1.2 seconds, $p < 0.01$; Cups: 13.9 ± 2.5 seconds versus 10.5 ± 1.3 seconds, $p < 0.0001$). The repeated study participants had longer phase durations than the original study participants, with all Grasp and Transport phases and the Movement 2 Release phase significantly prolonged in Pasta (Table 3-4), and all phases significantly prolonged in Cups (Table 3-5). The two participant groups, however, displayed similar relative phase durations throughout both tasks, with no significant differences.

Table 3-4: Pasta Box Transfer Task phase duration values with the significant results of the pairwise comparisons. For the results of the pairwise comparisons (in column *p*), * indicates a significant *p* value less than 0.05 and "ns" indicates a *p* value that is not significant.

		Duration (seconds)			Relative Duration (%)		
Movement	Phase	*p*	Original	Repeated	*p*	Original	Repeated
1	Reach	ns	0.66 ± 0.08	0.78 ± 0.18	ns	29.03 ± 2.01	27.48 ± 3.36
	Grasp	*	0.27 ± 0.08	0.40 ± 0.16	ns	11.47 ± 2.47	13.33 ± 2.89
	Transport	*	1.08 ± 0.12	1.34 ± 0.33	ns	47.13 ± 2.22	46.73 ± 2.09
	Release	ns	0.28 ± 0.07	0.37 ± 0.15	ns	12.37 ± 2.34	12.47 ± 2.45
2	Reach	ns	0.52 ± 0.06	0.61 ± 0.15	ns	24.44 ± 2.01	22.97 ± 2.21
	Grasp	*	0.18 ± 0.05	0.28 ± 0.11	ns	8.32 ± 1.67	9.95 ± 2.06
	Transport	*	1.12 ± 0.13	1.36 ± 0.32	ns	53.00 ± 2.89	51.03 ± 2.72
	Release	*	0.30 ± 0.08	0.44 ± 0.18	ns	14.24 ± 2.73	16.06 ± 2.76
3	Reach	ns	0.65 ± 0.10	0.76 ± 0.18	ns	26.18 ± 1.82	24.78 ± 1.91
	Grasp	*	0.19 ± 0.06	0.28 ± 0.12	ns	7.36 ± 1.78	8.57 ± 2.30
	Transport	*	1.31 ± 0.16	1.60 ± 0.34	ns	52.91 ± 2.07	52.37 ± 3.57
	Release	ns	0.34 ± 0.07	0.46 ± 0.19	ns	13.56 ± 2.16	14.73 ± 3.10

Table 3-5: Cup Transfer Task phase duration values with the significant results of the pairwise comparisons. For the results of the pairwise comparisons (in column *p*), * indicates a significant *p* value less than 0.05, ** indicates a *p* value less than 0.005, and "ns" indicates a *p* value that is not significant.

		Duration (seconds)			Relative Duration (%)		
Movement	Phase	*p*	Original	Repeated	*p*	Original	Repeated
1	Reach	*	0.66 ± 0.09	0.81 ± 0.19	ns	30.79 ± 1.72	29.04 ± 2.64
	Grasp	**	0.18 ± 0.05	0.28 ± 0.10	ns	8.38 ± 1.83	9.63 ± 2.17
	Transport	**	1.02 ± 0.10	1.23 ± 0.22	ns	47.77 ± 2.42	45.00 ± 4.68
	Release	**	0.28 ± 0.07	0.46 ± 0.14	ns	13.06 ± 2.34	16.34 ± 3.92
2	Reach	*	0.53 ± 0.09	0.66 ± 0.14	ns	24.00 ± 1.67	23.00 ± 2.43
	Grasp	*	0.23 ± 0.07	0.32 ± 0.09	ns	10.26 ± 1.92	11.04 ± 1.92
	Transport	**	1.15 ± 0.12	1.42 ± 0.20	ns	52.15 ± 2.72	49.94 ± 4.42
	Release	**	0.30 ± 0.07	0.47 ± 0.16	ns	13.59 ± 2.88	16.01 ± 4.20
3	Reach	**	0.88 ± 0.12	1.10 ± 0.24	ns	34.43 ± 2.03	33.62 ± 2.72
	Grasp	**	0.23 ± 0.06	0.32 ± 0.08	ns	9.06 ± 1.57	9.84 ± 1.65
	Transport	**	1.15 ± 0.12	1.39 ± 0.17	ns	45.30 ± 2.42	43.13 ± 4.06
	Release	**	0.29 ± 0.09	0.45 ± 0.16	ns	11.21 ± 3.00	13.40 ± 3.71
4	Reach	*	0.49 ± 0.06	0.59 ± 0.13	ns	24.91 ± 2.60	23.45 ± 3.01
	Grasp	**	0.15 ± 0.05	0.26 ± 0.09	ns	7.29 ± 1.71	9.89 ± 2.26
	Transport	**	1.04 ± 0.12	1.23 ± 0.17	ns	52.57 ± 2.65	49.41 ± 4.14
	Release	**	0.31 ± 0.09	0.45 ± 0.14	ns	15.23 ± 3.74	17.26 ± 3.91

3.4.2. Hand Movement

The repeated study participants had greater hand distances travelled than the original study participants, with significant increases in Movement 1 & 3 segments of Pasta (Table 3-6) and in all Cups movement segments, except for Movement 1 & 4 Transport-Releases (Table 3-7). However, Figure 3-3 (Pasta) and Figure 3-4 (Cups) show that the average hand trajectories chosen by both participant groups were similar. The repeated study participants also had larger hand trajectory variability than the original study participants, with significant increases in all Pasta movement segments except for Movement 3 Transport-Release (Table 3-6) and all Cups movement segments (Table 3-7). The repeated study participants had a greater number of movement units than the original study participants, with significant increases in all movement segments of Pasta and for Movement 1 & 4 Reach-Grasps and Movement 1 to 3 Transport-Releases of Cups.

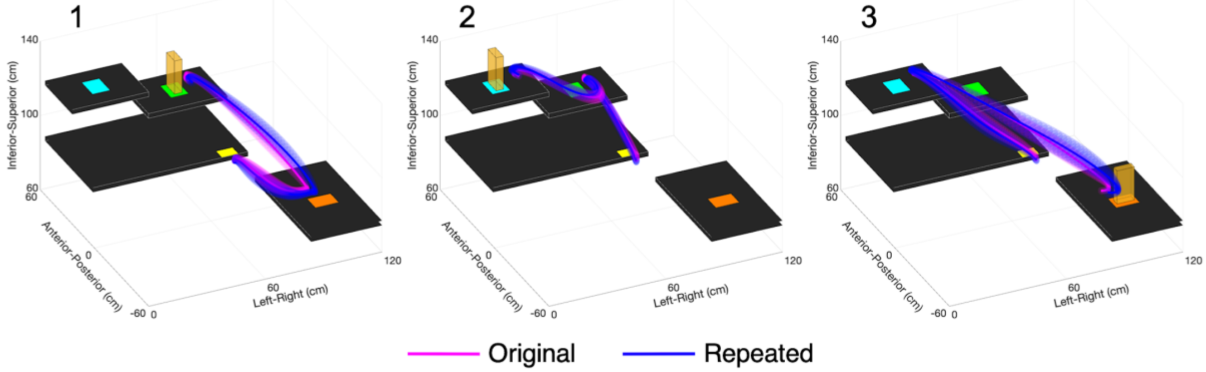

Figure 3-3: Pasta Box Transfer Task hand trajectories of participants in the original (pink) and repeated (blue) studies for Movements 1, 2, and 3. The solid lines represent participant group averages, and the three-dimensional shading represents the standard deviation of participant group means.

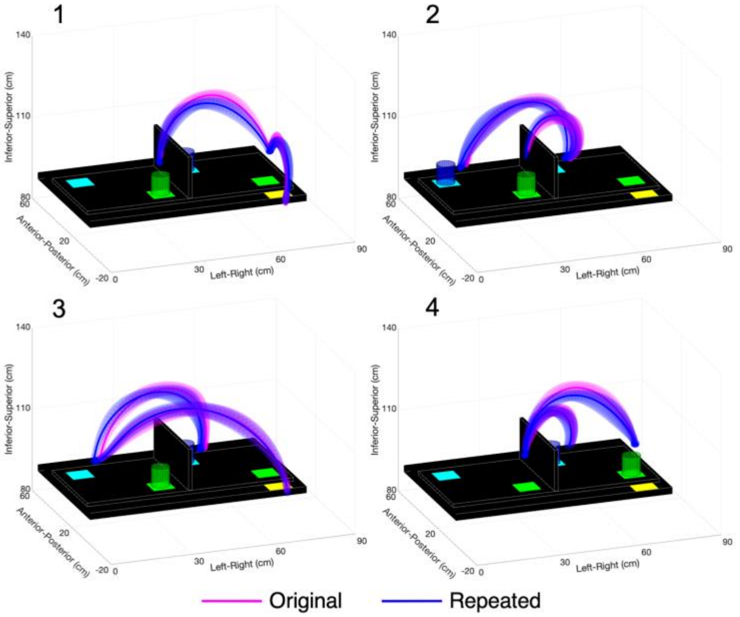

Figure 3-4: Cup Transfer Task hand trajectories of participants in the original (pink) and repeated (blue) studies for Movements 1, 2, 3, and 4. The solid lines represent participant group averages, and the three-dimensional shading represents the standard deviation of participant group means.

Table 3-6: Pasta Box Transfer Task hand movement values for each movement (‘M’) and movement segment (‘Seg’) with the significant results of the pairwise comparisons. For the results of the pairwise comparisons (in column *p*), * indicates a significant *p* value less than 0.05, ** indicates a *p* value less than 0.005, and “ns” indicates a *p* value that is not significant.

		Hand Distance Travelled (mm)			Hand Trajectory Variability (mm)			Number of Movement Units		
M	Seg	*p*	Original	Repeated	*p*	Original	Repeated	*p*	Original	Repeated
1	RG	**	492 ± 26	539 ± 36	*	19 ± 5	30 ± 12	*	1.3 ± 0.3	1.6 ± 0.4
	TRL	*	935 ± 27	964 ± 25	**	22 ± 4	30 ± 6	*	1.2 ± 0.2	1.8 ± 0.7
2	RG	ns	505 ± 23	506 ± 24	*	15 ± 5	23 ± 8	*	1.0 ± 0.1	1.1 ± 0.1
	TRL	ns	802 ± 61	819 ± 31	**	20 ± 4	27 ± 5	*	2.3 ± 0.4	3.0 ± 0.8
3	RG	**	746 ± 24	796 ± 25	*	19 ± 4	28 ± 10	*	1.1 ± 0.1	1.3 ± 0.3
	TRL	**	1186 ± 31	1278 ± 52	ns	35 ± 8	47 ± 18	*	1.7 ± 0.4	2.4 ± 0.9
		Peak Hand Velocity (mm/s)			Percent-to-Peak Hand Velocity (%)					
M	Seg	*p*	Original	Repeated	*p*	Original	Repeated			
1	RG	ns	1164 ± 163	1098 ± 225	*	41.2 ± 4.5	45.0 ± 4.0			
	TRL	ns	1447 ± 136	1359 ± 319	ns	29.3 ± 3.1	27.0 ± 3.6			
2	RG	ns	1352 ± 191	1200 ± 238	ns	36.8 ± 4.4	34.3 ± 4.6			
	TRL	ns	1069 ± 112	900 ± 210	ns	44.8 ± 8.6	44.0 ± 11.8			
3	RG	ns	1666 ± 261	1585 ± 343	ns	35.5 ± 4.0	32.4 ± 5.1			
	TRL	ns	1598 ± 180	1477 ± 273	ns	36.2 ± 3.8	37.8 ± 4.1			
		Peak Grip Aperture (mm)			Percent-to-Peak Grip Aperture (%)			Percent-to-Peak Hand Deceleration (%)		
M	Seg	*p*	Original	Repeated	*p*	Original	Repeated	*p*	Original	Repeated
1	RG	ns	116 ± 8	109 ± 11	ns	73.3 ± 6.5	77.8 ± 6.3	ns	55.7 ± 8.0	58.2 ± 5.4
2	RG	ns	106 ± 10	104 ± 11	ns	80.1 ± 8.0	79.8 ± 8.9	ns	72.6 ± 8.6	65.1 ± 13.2
3	RG	ns	109 ± 8	108 ± 10	ns	81.5 ± 4.9	83.3 ± 6.7	ns	72.8 ± 8.4	64.3 ± 13.5

Table 3-7: Cup Transfer Task hand movement values for each movement (‘M’) and movement segment (‘Seg’) with the significant results of the pairwise comparisons. For the results of the pairwise comparisons (in column *p*), * indicates a significant *p* value less than 0.05, ** indicates a *p* value less than 0.005, and “ns” indicates a *p* value that is not significant.

		Hand Distance Travelled (mm)			Hand Trajectory Variability (mm)			Number of Movement Units		
M	Seg	*p*	Original	Repeated	*p*	Original	Repeated	*p*	Original	Repeated
1	RG	**	366 ± 52	371 ± 34	*	16 ± 3	21 ± 6	*	1.4 ± 0.4	1.9 ± 0.5
	TRL	ns	646 ± 39	652 ± 30	*	17 ± 4	22 ± 5	*	2.3 ± 0.4	2.8 ± 0.7
2	RG	**	456 ± 56	516 ± 44	*	17 ± 4	22 ± 5	ns	1.2 ± 0.3	1.5 ± 0.4
	TRL	*	700 ± 46	729 ± 39	*	20 ± 5	26 ± 6	*	2.4 ± 0.4	3.1 ± 0.9
3	RG	**	887 ± 35	949 ± 51	*	26 ± 5	35 ± 11	ns	1.6 ± 0.3	1.7 ± 0.3
	TRL	**	724 ± 46	755 ± 44	*	20 ± 4	26 ± 6	*	2.1 ± 0.6	2.7 ± 0.9
4	RG	**	428 ± 49	480 ± 45	*	14 ± 4	20 ± 7	*	1.1 ± 0.2	1.4 ± 0.3
	TRL	ns	657 ± 46	665 ± 34	*	20 ± 4	27 ± 8	ns	2.4 ± 0.4	2.8 ± 0.6
		Peak Hand Velocity (mm/s)			Percent-to-Peak Hand Velocity (%)					
M	Seg	*p*	Original	Repeated	*p*	Original	Repeated			
1	RG	ns	866 ± 166	808 ± 191	ns	35.2 ± 4.4	35.2 ± 5.0			
	TRL	ns	1042 ± 88	931 ± 132	ns	21.0 ± 2.6	19.9 ± 2.5			
2	RG	ns	1149 ± 139	1130 ± 267	*	30.3 ± 7.2	25.0 ± 3.8			
	TRL	ns	940 ± 70	820 ± 107	ns	37.7 ± 9.1	31.3 ± 8.2			
3	RG	ns	1492 ± 187	1396 ± 287	*	36.3 ± 8.4	30.0 ± 4.1			
	TRL	ns	1009 ± 56	883 ± 98	ns	24.7 ± 2.4	25.0 ± 3.5			
4	RG	ns	1157 ± 147	1177 ± 230	ns	24.5 ± 4.7	25.0 ± 5.3			
	TRL	ns	979 ± 76	874 ± 110	ns	28.0 ± 7.6	30.8 ± 6.7			
		Peak Grip Aperture (mm)			Percent-to-Peak Grip Aperture (%)			Percent-to-Peak Hand Deceleration (%)		
M	Seg	*p*	Original	Repeated	*p*	Original	Repeated	*p*	Original	Repeated
1	RG	ns	99 ± 4	97 ± 7	ns	80.4 ± 4.7	77.6 ± 4.2	ns	62.0 ± 8.7	56.0 ± 9.6
2	RG	ns	114 ± 6	114 ± 9	ns	73.0 ± 6.3	71.4 ± 8.0	ns	49.8 ± 6.5	46.7 ± 4.6
3	RG	ns	114 ± 7	113 ± 7	ns	80.4 ± 3.9	78.7 ± 5.3	ns	61.0 ± 5.3	57.4 ± 5.1
4	RG	ns	100 ± 5	101 ± 6	*	83.7 ± 5.4	76.5 ± 7.4	*	62.3 ± 13.5	50.6 ± 8.7

Participants in the original and repeated studies had similar hand velocity profiles for both tasks, as shown in Figure 3-5. Although the peaks in the repeated study appeared smaller, these differences were non-significant throughout both tasks (Table 3-6 and Table 3-7). Significant percent-to-peak hand velocity differences were identified for the Movement 1 Reach-Grasp segment of Pasta and the Movement 2 & 3 Reach-Grasp segments of Cups, but the differences between the mean values of the two participant groups were less than one standard deviation of the original study results. Participants in the original and repeated studies showed similar percent-to-peak hand deceleration values, with no significant differences in Pasta and a significantly difference only for the Movement 4 Reach-Grasp segment of Cups. However, the difference between the mean values of the two participant groups in this movement segment was less than one original study standard deviation.

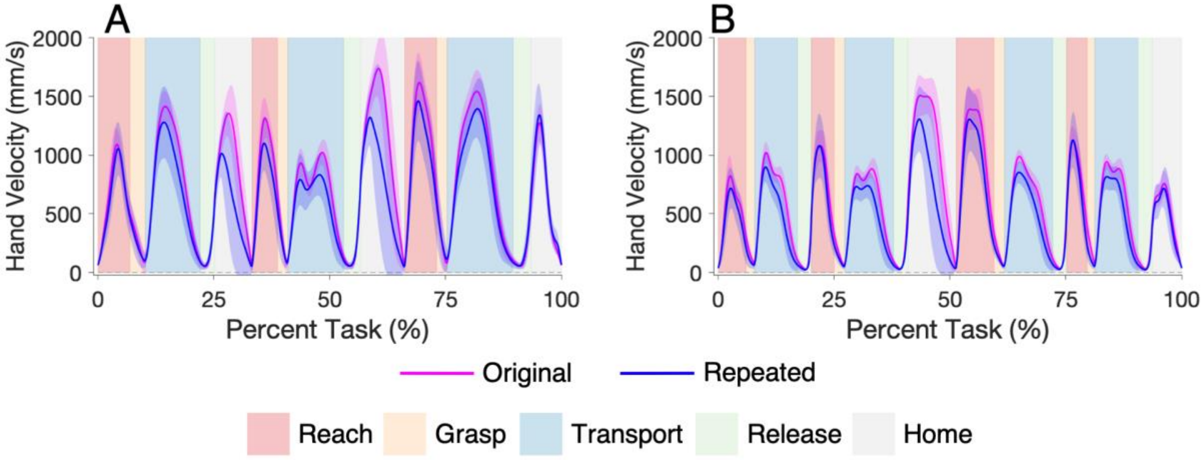

Figure 3-5: Hand velocity profiles of participants in the original (pink) and repeated (blue) studies for the Pasta Box Transfer Task (A) and the Cup Transfer Task (B). The solid lines represent participant group averages, and the shading represents the standard deviation of the participant group means. This task is segmented into Reach (red), Grasp (orange), Transport (blue), Release (green), and Home (grey) phases for each movement.

Participants in the original and repeated studies had similar grip aperture profiles for both tasks, as shown in Figure 3-6, with no significant differences in peak grip aperture identified with either task. Also, no significant differences in percent-to-peak grip aperture were identified in Pasta, and a significant difference was only identified in the Movement 4 Reach-Grasp segment of Cups.

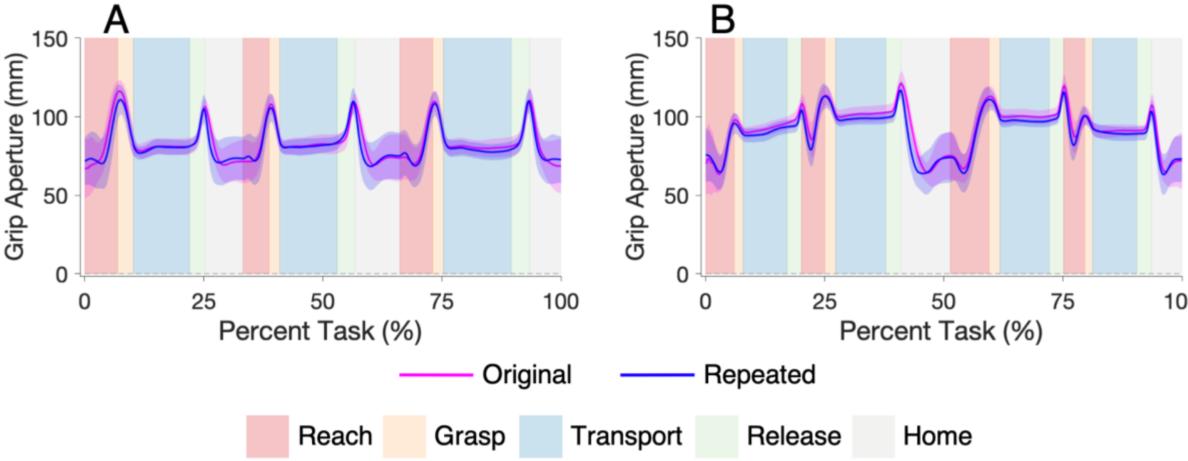

Figure 3-6: Grip aperture profiles of participants in the original (pink) and repeated (blue) studies for the Pasta Box Transfer Task (A) and the Cup Transfer Task (B). The solid lines represent participant group averages, and the shading represents the standard deviation of the participant group means. This task is segmented into Reach (red), Grasp (orange), Transport (blue), Release (green), and Home (grey) phases for each movement.

3.4.3. Angular Joint Kinematics

Angular kinematic trajectories illustrating the average joint trajectories of participants are shown in Figure 3-7 (Pasta) and Figure 3-8 (Cups). Similar angular kinematic profiles existed between the original and repeated study participants, with only a few differences; participants in the repeated study had an increased standard deviation for trunk flexion/extension (both tasks), and an offset was present between the wrist flexion/extension angles (both tasks) and between the wrist ulnar/radial deviations angles (Pasta only) of the two participant groups. Angular kinematic measures are presented in Table 3-8 (Pasta) and Table 3-9 (Cups). The original and repeated study participants generally had similar peak joint angles in both tasks. Significant peak angle differences were found in wrist flexion/extension for Movements 1 and 2 of Pasta and all movements of Cups, and in wrist radial/ulnar deviation for all movements of Pasta.

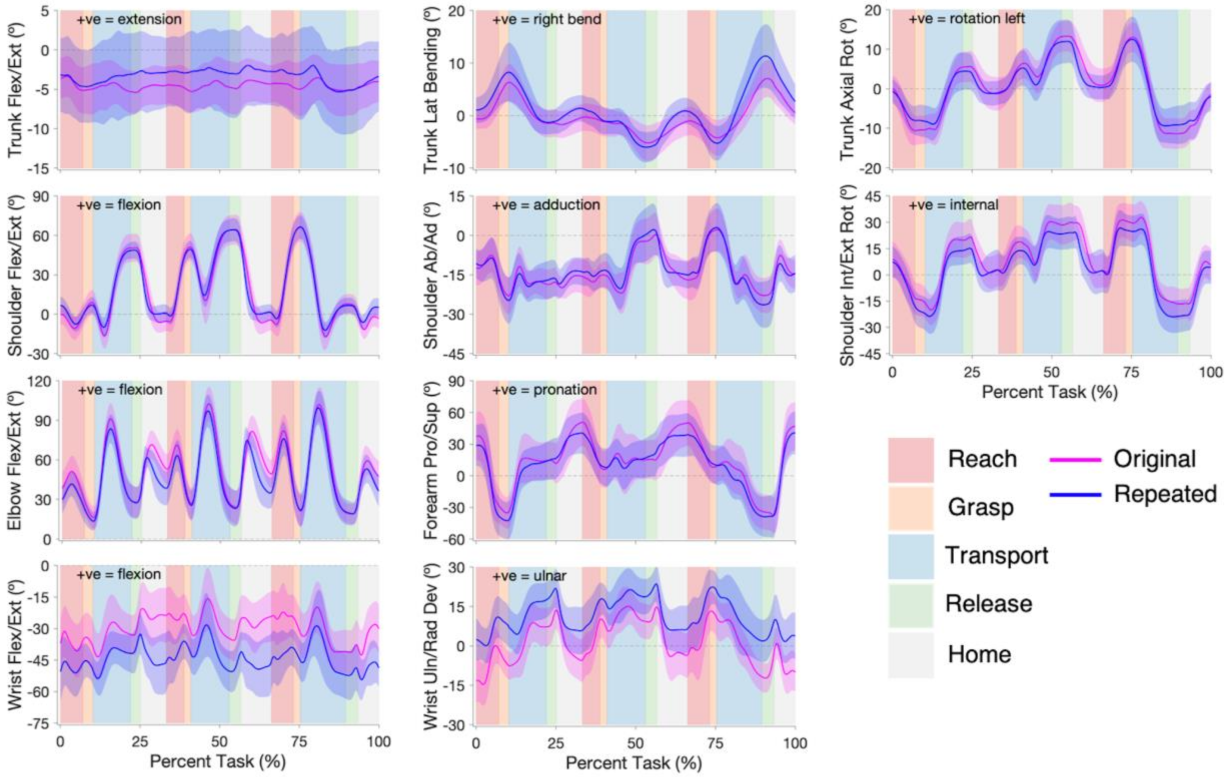

Figure 3-7: Pasta Box Transfer Task angular joint trajectories in the original (pink) and repeated (blue) studies for trunk flexion/extension, lateral bending, and axial rotation; shoulder flexion/extension, abduction/adduction, and internal/external rotation; elbow flexion/extension and forearm pronation/supination; and wrist flexion/extension and ulnar/radial deviation. The solid lines represent participant group averages, and the shading represents the standard deviation of the participant group means. This task is segmented into Reach (red), Grasp (orange), Transport (blue), Release (green), and Home (grey) phases for each movement.

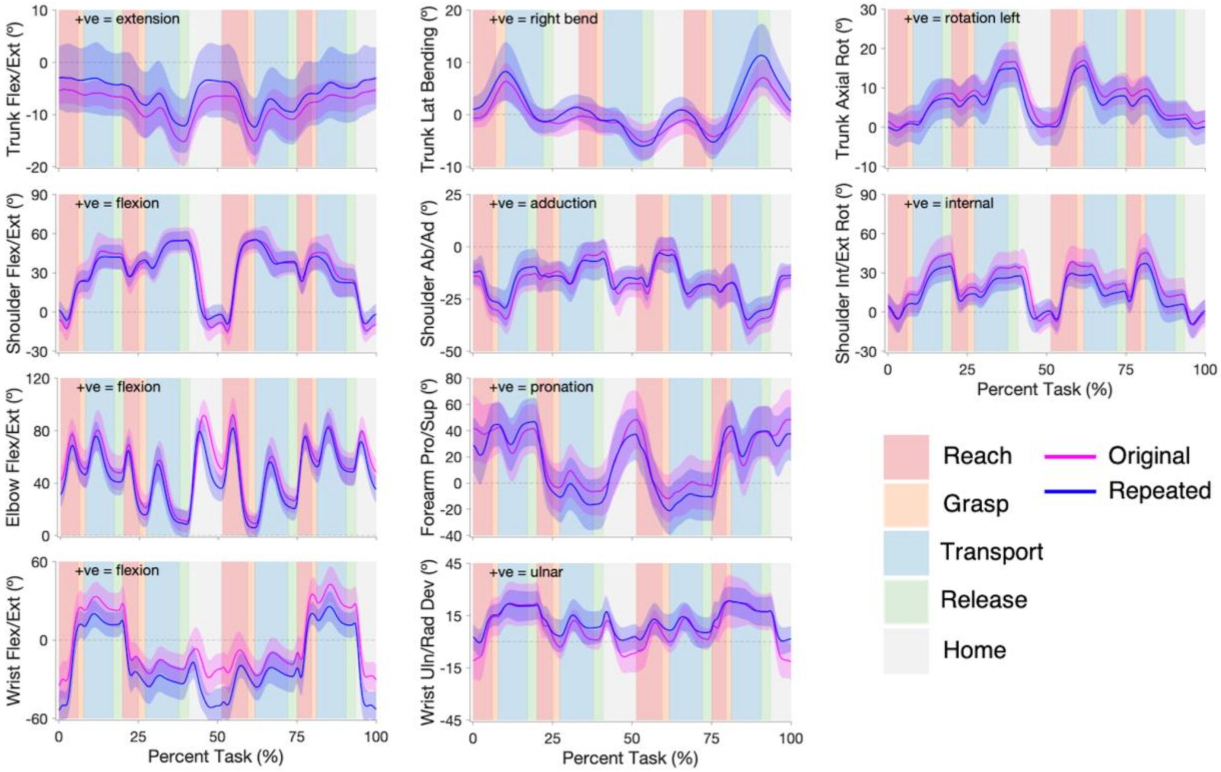

Figure 3-8: Cup Transfer Task angular joint trajectories in the original (pink) and repeated (blue) studies for trunk flexion/extension, lateral bending, and axial rotation; shoulder flexion/extension, abduction/adduction, and internal/external rotation; elbow flexion/extension and forearm pronation/supination; and wrist flexion/extension and ulnar/radial deviation. The solid lines represent participant group averages, and the shading represents the standard deviation of the participant group means. This task is segmented into Reach (red), Grasp (orange), Transport (blue), Release (green), and Home (grey) phases for each movement.

Table 3-8: Pasta Box Transfer Task angular joint kinematic values with the significant results of the initial RMANOVAs and pairwise comparisons. Angular kinematic values include peak angle (degrees), range of motion (degrees), and peak angular velocity (degrees/s) of each movement (M) for trunk flexion/extension (FE), lateral bending (LB), and axial rotation (AR); shoulder (Sho) flexion/extension, abduction/adduction (AA), and internal/external rotation (IER); elbow flexion/extension and forearm pronation/supination (Frm PS); and wrist flexion/extension and radial/ulnar deviation (RUD). For the results of the pairwise comparisons (in column *p*), * indicates a *p* value less than 0.05, ** indicates a *p* value less than 0.005, and ns indicates a *p* value that is not significant. Highlighted table cells also indicate significant differences (red = higher and blue = lower repeated study value).

		Peak Angle (degrees)			Range of Motion (degrees)			Peak Angular Velocity (degrees/s)		
	M	*p*	Original	Repeated	*p*	Original	Repeated	*p*	Original	Repeated
Trunk FE	1	ns	-2.1 ± 2.4	-0.9 ± 4.7	ns	4.9 ± 1.6	6.0 ± 2.2	ns	18.8 ± 5.4	23.7 ± 7.8
	2	ns	-2.7 ± 2.6	0.2 ± 5.0	*	3.6 ± 1.0	5.8 ± 2.5	*	14.9 ± 5.4	22.9 ± 8.4
	3	ns	-2.1 ± 2.5	0.2 ± 5.0	ns	4.9 ± 1.4	7.3 ± 4.2	*	18.2 ± 5.0	28.4 ± 13.6
Trunk LB	1	ns	6.5 ± 3.5	8.6 ± 5.4	ns	8.7 ± 2.8	10.2 ± 4.2	ns	21.7 ± 5.5	19.9 ± 8.0
	2	ns	0.2 ± 2.5	1.7 ± 2.4	*	5.6 ± 2.0	8.2 ± 2.6	ns	12.8 ± 3.6	15.0 ± 3.7
	3	ns	7.2 ± 3.5	11.6 ± 6.0	*	11.8 ± 2.8	17.3 ± 6.6	ns	21.3 ± 3.9	24.2 ± 6.6
Trunk AR	1	ns	6.0 ± 3.9	5.0 ± 4.6	ns	17.8 ± 2.4	14.9 ± 4.9	ns	42.6 ± 6.6	37.0 ± 11.1
	2	ns	13.7 ± 3.9	12.4 ± 5.5	ns	15.1 ± 3.0	13.8 ± 4.6	ns	33.4 ± 8.3	36.8 ± 13.6
	3	ns	13.3 ± 3.8	12.9 ± 5.8	ns	25.5 ± 3.0	24.1 ± 8.2	ns	58.6 ± 10.8	52.3 ± 17.1
Sho FE	1	ns	51.3 ± 10.6	49.3 ± 6.5	ns	69.3 ± 7.6	61.4 ± 8.5	*	192.3 ± 39.4	143.8 ± 44.1
	2	ns	64.9 ± 11.4	64.7 ± 8.7	ns	72.1 ± 9.7	67.1 ± 9.9	*	200.8 ± 40.9	154.1 ± 45.0
	3	ns	66.8 ± 11.2	67.0 ± 8.8	ns	86.0 ± 9.9	81.7 ± 10.1	ns	233.0 ± 40.4	192.8 ± 54.2
Sho AA	1	ns	-5.8 ± 5.1	-6.1 ± 6.8	ns	19.3 ± 6.5	20.1 ± 5.2	ns	76.6 ± 23.6	65.6 ± 27.0
	2	ns	1.4 ± 7.2	3.1 ± 9.4	ns	25.6 ± 8.8	25.6 ± 8.0	ns	81.5 ± 30.7	69.7 ± 21.3
	3	ns	3.5 ± 6.9	4.0 ± 8.6	ns	28.9 ± 9.1	32.0 ± 10.5	ns	101.7 ± 27.6	90.0 ± 24.3
Sho IER	1	ns	22.8 ± 10.0	16.4 ± 8.4	ns	44.0 ± 7.9	41.5 ± 9.2	*	151.1 ± 32.3	112.5 ± 40.8
	2	ns	32.6 ± 10.4	27.3 ± 9.6	ns	32.6 ± 6.7	27.8 ± 6.9	*	123.3 ± 23.1	89.4 ± 34.4
	3	ns	34.9 ± 9.6	29.7 ± 9.7	ns	54.2 ± 6.8	55.7 ± 10.2	ns	180.4 ± 33.8	148.9 ± 44.4
Elbow FE	1	ns	92.1 ± 11.9	85.4 ± 11.5	ns	76.4 ± 10.6	73.1 ± 10.2	*	274.2 ± 53.8	218.5 ± 62.1
	2	ns	103.6 ± 12.8	98.6 ± 12.7	ns	81.2 ± 9.6	78.8 ± 9.6	ns	268.1 ± 47.5	226.1 ± 51.4
	3	ns	103.8 ± 13.2	102.3 ± 12.2	ns	88.4 ± 11.6	87.4 ± 11.3	ns	270.3 ± 48.6	226.8 ± 55.2
Frm PS	1	ns	40.1 ± 22.5	33.8 ± 20.2	ns	77.0 ± 15.9	78.9 ± 19.0	*	308.6 ± 70.4	244.7 ± 72.5
	2	ns	51.3 ± 22.3	44.7 ± 20.2	ns	51.4 ± 18.2	47.1 ± 12.4	ns	176.4 ± 57.6	149.2 ± 51.7
	3	ns	51.4 ± 21.7	42.7 ± 19.9	ns	90.9 ± 17.3	85.3 ± 16.4	ns	181.8 ± 47.9	169.5 ± 62.2
Wrist FE	1	*	-18.6 ± 12.4	-29.1 ± 8.7	ns	28.6 ± 6.1	31.0 ± 8.4	*	136.8 ± 30.4	109.3 ± 27.2
	2	*	-11.8 ± 13.8	-23.5 ± 12.2	ns	25.5 ± 8.9	32.0 ± 10.3	ns	122.3 ± 36.4	119.6 ± 37.0
	3	ns	-12.6 ± 11.4	-22.5 ± 15.3	ns	32.3 ± 8.0	36.4 ± 14.7	ns	123.9 ± 38.6	123.0 ± 42.6
Wrist URD	1	*	14.6 ± 7.8	*23.1 ± 7.1	ns	30.9 ± 5.6	25.7 ± 7.4	*	108.9 ± 39.3	77.7 ± 30.1
	2	*	18.8 ± 7.8	*26.4 ± 6.8	ns	24.7 ± 7.3	22.4 ± 7.6	*	95.6 ± 23.0	69.1 ± 24.1
	3	*	16.3 ± 7.3	*24.6 ± 7.0	ns	29.7 ± 4.7	26.4 ± 5.8	*	117.5 ± 28.0	88.8 ± 30.8

Table 3-9: Cup Transfer Task angular joint kinematic values with the significant results of the initial RMANOVAs and pairwise comparisons. Angular kinematic values include peak angle (degrees), range of motion (degrees), and peak angular velocity (degrees/s) of each movement (M) for trunk flexion/extension (FE), lateral bending (LB), and axial rotation (AR); shoulder (Sho) flexion/extension, abduction/adduction (AA), and internal/external rotation (IER); elbow flexion/extension and forearm pronation/supination (Frm PS); and wrist flexion/extension and radial/ulnar deviation (RUD). For the results of the pairwise comparisons (in column *p*), * indicates a *p* value less than 0.05, ** indicates a *p* value less than 0.005, and ns indicates a *p* value that is not significant. Highlighted table cells also indicate significant differences (red = higher and blue = lower repeated study value).

		Peak Angle (degrees)			Range of Motion (degrees)			Peak Angular Velocity (degrees/s)		
	M	*p*	Original	Repeated	*p*	Original	Repeated	*p*	Original	Repeated
Trunk FE	1	ns	-4.4 ± 2.5	-1.2 ± 6.2	*	3.0 ± 1.5	4.7 ± 1.9	**	10.7 ± 3.4	16.0 ± 4.7
	2	ns	-6.3 ± 2.5	-2.9 ± 5.7	ns	9.1 ± 3.3	10.2 ± 2.5	ns	23.1 ± 6.8	25.2 ± 6.4
	3	ns	-5.6 ± 2.8	-2.1 ± 6.1	ns	9.6 ± 3.1	11.2 ± 3.2	ns	27.2 ± 7.8	31.8 ± 12.2
	4	ns	-5.7 ± 2.7	-3.0 ± 6.5	ns	4.7 ± 2.5	6.0 ± 1.5	ns	13.0 ± 4.1	16.6 ± 5.3
Trunk LB	1	ns	-0.4 ± 1.8	1.9 ± 3.9	**	4.8 ± 1.9	7.7 ± 2.3	ns	9.9 ± 3.6	12.0 ± 3.4
	2	ns	0.3 ± 4.1	1.9 ± 4.6	ns	7.2 ± 2.4	9.5 ± 3.6	ns	16.5 ± 6.0	19.0 ± 8.1
	3	ns	-0.6 ± 3.2	2.2 ± 4.1	**	6.2 ± 1.9	9.4 ± 3.3	ns	15.1 ± 3.7	20.9 ± 10.3
	4	ns	-1.1 ± 3.0	0.8 ± 4.4	*	4.0 ± 1.4	5.7 ± 2.0	ns	10.8 ± 3.4	12.9 ± 5.3
Trunk AR	1	ns	8.9 ± 3.7	7.7 ± 5.1	ns	9.3 ± 2.5	9.2 ± 2.7	ns	20.6 ± 4.0	21.5 ± 5.2
	2	ns	17.1 ± 5.0	15.7 ± 4.7	ns	10.7 ± 2.8	11.3 ± 3.4	ns	28.1 ± 7.4	30.1 ± 9.3
	3	ns	17.2 ± 5.0	16.4 ± 5.0	ns	16.7 ± 4.2	16.9 ± 4.7	ns	39.1 ± 9.8	44.2 ± 15.9
	4	ns	10.3 ± 3.9	8.6 ± 4.8	ns	7.9 ± 2.4	7.2 ± 2.3	ns	22.6 ± 7.3	22.2 ± 6.7
Sho FE	1	ns	49.2 ± 14.6	43.9 ± 9.1	*	62.7 ± 13.5	50.8 ± 11.4	*	142.1 ± 42.8	104.5 ± 31.7
	2	ns	56.8 ± 10.4	55.7 ± 7.3	ns	30.9 ± 6.2	29.6 ± 4.9	ns	103.9 ± 29.7	77.9 ± 31.7
	3	ns	57.5 ± 11.0	56.4 ± 7.5	ns	73.6 ± 10.4	66.6 ± 8.9	*	228.2 ± 58.8	174.3 ± 61.6
	4	ns	49.5 ± 14.8	43.7 ± 10.7	ns	29.6 ± 9.0	26.4 ± 8.6	ns	104.7 ± 25.0	95.2 ± 34.5
Sho AA	1	ns	-8.1 ± 4.7	-6.3 ± 6.2	ns	27.5 ± 7.1	23.7 ± 5.4	ns	80.4 ± 23.4	65.8 ± 19.7
	2	ns	-1.4 ± 5.9	-3.4 ± 8.2	ns	18.7 ± 5.6	16.2 ± 4.2	*	63.7 ± 17.1	49.3 ± 14.3
	3	ns	0.1 ± 5.5	-1.1 ± 7.7	ns	28.7 ± 8.6	23.9 ± 6.3	ns	98.1 ± 34.9	79.3 ± 33.0
	4	ns	-13.9 ± 6.9	-14.4 ± 7.1	ns	26.1 ± 6.0	21.7 ± 5.8	*	74.9 ± 19.4	59.3 ± 16.5
Sho IER	1	ns	44.9 ± 14.9	35.5 ± 10.9	ns	51.5 ± 13.9	41.2 ± 10.6	*	116.0 ± 57.8	74.1 ± 23.8
	2	ns	43.6 ± 13.8	34.8 ± 10.2	ns	33.1 ± 7.5	28.2 ± 6.5	**	180.2 ± 36.3	120.5 ± 43.1
	3	ns	41.8 ± 13.8	32.4 ± 10.1	*	49.9 ± 12.2	38.8 ± 10.4	*	188.8 ± 56.6	131.8 ± 49.3
	4	ns	46.6 ± 14.7	37.9 ± 11.8	ns	39.5 ± 9.6	36.6 ± 8.5	*	160.1 ± 39.0	120.4 ± 41.4
Elbow FE	1	ns	84.7 ± 12.3	78.5 ± 11.7	ns	44.6 ± 9.4	48.8 ± 10.7	ns	173.4 ± 44.5	150.6 ± 39.0
	2	ns	70.6 ± 11.6	66.6 ± 11.7	ns	60.4 ± 8.1	58.8 ± 8.2	ns	196.8 ± 30.6	174.5 ± 39.5
	3	ns	93.3 ± 12.9	84.0 ± 11.2	ns	84.6 ± 9.3	78.7 ± 11.8	*	281.1 ± 59.3	226.6 ± 63.3
	4	ns	84.7 ± 13.4	84.3 ± 11.6	ns	48.3 ± 6.0	53.5 ± 6.9	ns	227.7 ± 43.2	213.9 ± 43.6
Frm PS	1	ns	50.7 ± 21.5	50.2 ± 17.7	ns	31.0 ± 11.5	36.3 ± 11.2	ns	113.9 ± 24.3	125.4 ± 37.1
	2	ns	36.7 ± 19.5	43.2 ± 18.6	**	46.9 ± 12.6	62.9 ± 15.0	ns	182.4 ± 44.5	190.5 ± 69.2
	3	ns	49.7 ± 22.2	38.8 ± 19.9	ns	64.2 ± 11.5	62.5 ± 17.9	ns	196.2 ± 49.1	154.7 ± 52.7
	4	ns	43.3 ± 21.0	45.1 ± 19.8	ns	46.6 ± 9.7	56.6 ± 15.0	ns	188.6 ± 67.7	184.0 ± 50.4
Wrist FE	1	**	35.6 ± 11.4	22.8 ± 10.5	ns	74.2 ± 14.4	81.0 ± 16.4	ns	283.1 ± 74.0	259.6 ± 68.2
	2	*	28.4 ± 13.6	14.8 ± 10.2	ns	57.2 ± 7.4	55.2 ± 11.5	ns	276.5 ± 78.2	219.9 ± 87.4
	3	*	0.9 ± 14.9	-12.7 ± 10.5	ns	34.6 ± 10.9	41.9 ± 11.1	ns	162.9 ± 65.2	138.2 ± 37.0
	4	**	44.5 ± 13.6	28.6 ± 10.9	ns	61.7 ± 10.1	58.6 ± 13.1	*	299.9 ± 63.0	237.5 ± 65.5
Wrist URD	1	ns	24.6 ± 11.4	24.3 ± 7.5	**	37.7 ± 8.5	26.4 ± 8.2	**	134.9 ± 34.7	81.9 ± 26.4
	2	ns	23.6 ± 9.6	24.2 ± 7.6	ns	27.7 ± 6.1	23.1 ± 7.7	**	122.5 ± 35.3	84.1 ± 26.9
	3	ns	15.8 ± 7.4	18.1 ± 8.2	ns	25.1 ± 6.2	20.6 ± 6.3	**	115.0 ± 35.4	73.7 ± 22.1
	4	ns	26.9 ± 11.7	26.5 ± 7.8	ns	23.5 ± 6.0	20.5 ± 8.8	*	126.4 ± 33.9	91.8 ± 34.6

The original and repeated study participants also had similar ranges of motion (ROMs) in Pasta, although significant differences were found for the Movement 2 trunk flexion/extension ROM and the Movement 2 & 3 trunk lateral bending ROM. However, these differences were quite small (with the largest being 5.3°). In Cups, differences in ROMs were significant in more movements and DOFs, as indicated by the shading in Table 3-9. However, the significant trunk ROM differences were quite small (both less than 2°), and the significant shoulder ROM differences were less than the respective original study standard deviations for those DOFs.

The repeated study participants exhibited differences in peak angular velocities in most DOFs in both tasks. The peak angular velocities in the trunk DOFs of repeated study participants were usually greater than those of original study participants, with significant trunk flexion/extension differences in Movement 1 and 2 of Pasta and Movement 1 of Cups. The peak angular velocities in the remaining DOFs of the repeated study participants were usually smaller than for the original study participants, with most significantly lower.

3.4.4. Eye Gaze

The repeated and original study participants exhibited similar eye fixations, with no significant differences identified in either task, as shown in Table 3-10 (Pasta) and Table 3-11 (Cups). Significant eye arrival latency differences were identified in all Grasp phase transitions and the Movement 3 Release phase transition of Pasta, as well as the Movement 3 phase transitions of Cups. No significant eye leaving latency differences were identified in Pasta, but significant differences were identified in the Movement 3 Release transition in Cups.

Table 3-10: Pasta Box Transfer Task eye movement values with the significant results of the pairwise comparisons. For the results of the pairwise comparisons (in column *p*), * indicates a significant *p* value less than 0.05 and "ns" indicates a *p* value that is not significant.

		Percent Fixation to Current (%)			Number of Fixations to Current		
Movement	Phase	*p*	Original	Repeated	*p*	Original	Repeated
1	Reach	ns	42.8 ± 8.6	49.4 ± 13.6	ns	1.01 ± 0.14	1.02 ± 0.05
	Grasp	ns	82.7 ± 15.0	73.9 ± 20.4	ns	0.97 ± 0.07	0.98 ± 0.04
	Transport	ns	75.1 ± 9.7	78.3 ± 9.1	ns	1.03 ± 0.05	1.05 ± 0.07
	Release	ns	71.8 ± 18.0	72.7 ± 25.1	ns	0.99 ± 0.03	1.02 ± 0.15
2	Reach	ns	77.5 ± 15.0	86.4 ± 14.9	ns	1.00 ± 0.02	1.02 ± 0.08
	Grasp	ns	89.4 ± 15.3	81.3 ± 19.9	ns	0.93 ± 0.15	0.90 ± 0.21
	Transport	ns	76.9 ± 9.3	81.0 ± 10.8	ns	1.02 ± 0.06	1.05 ± 0.06
	Release	ns	81.8 ± 15.1	81.5 ± 18.7	ns	0.99 ± 0.03	1.05 ± 0.21
3	Reach	ns	66.4 ± 15.8	80.4 ± 17.5	ns	1.02 ± 0.04	1.05 ± 0.13
	Grasp	ns	93.6 ± 14.0	91.6 ± 13.4	ns	0.98 ± 0.05	1.02 ± 0.08
	Transport	ns	50.0 ± 4.7	54.1 ± 8.7	ns	1.06 ± 0.09	1.10 ± 0.08
	Release	ns	64.2 ± 15.8	63.2 ± 20.0	ns	1.00 ± 0.09	0.97 ± 0.16
		Percent Fixation to Hand Only (%)			Number of Fixations to Hand Only		
Movement	Phase	*p*	Original	Repeated	*p*	Original	Repeated
1	Reach	ns		14.5 ± 1.8	ns	0.00 ± 0.00	0.03 ± 0.08
	Transport	ns	5.8 ± 2.4	9.3 ± 6.4	ns	0.32 ± 0.33	0.29 ± 0.29
2	Reach	ns	10.5 ± 9.0	5.1 ± 0.0	ns	0.03 ± 0.10	0.01 ± 0.05
	Transport	ns	12.7 ± 6.7	11.0 ± 6.5	ns	0.75 ± 0.28	0.64 ± 0.38
3	Reach	ns	10.5 ± 7.7	6.2 ± 1.9	ns	0.07 ± 0.19	0.09 ± 0.16
	Transport	ns	11.2 ± 3.6	10.9 ± 3.7	ns	0.85 ± 0.27	0.83 ± 0.26
		Eye Arrival Latency (seconds)			Eye Leaving Latency (seconds)		
Movement	Transition	*p*	Original	Repeated	*p*	Original	Repeated
1	Grasp	*	0.55 ± 0.11	0.79 ± 0.28	ns	0.02 ± 0.08	0.01 ± 0.15
	Release	ns	0.82 ± 0.20	1.04 ± 0.26	ns	-0.30 ± 0.20	-0.55 ± 0.64
2	Grasp	*	0.58 ± 0.14	0.82 ± 0.28	ns	-0.09 ± 0.13	-0.06 ± 0.16
	Release	ns	0.87 ± 0.17	1.1 ± 0.31	ns	-0.34 ± 0.19	-0.67 ± 0.67
3	Grasp	*	0.62 ± 0.17	0.91 ± 0.36	ns	-0.12 ± 0.09	-0.14 ± 0.15
	Release	*	0.66 ± 0.10	0.90 ± 0.25	ns	-0.23 ± 0.09	-0.34 ± 0.25

Table 3-11: Cup Transfer Task eye movement values with the significant results of the pairwise comparisons. For the results of the pairwise comparisons (in column *p*), * indicates a significant p value less than 0.05 and "ns" indicates a p value that is not significant.

		Percent Fixation to Current (%)			Number of Fixations to Current		
Movement	Phase	*p*	Original	Repeated	*p*	Original	Repeated
1	Reach	ns	71.8 ± 14.6	68.3 ± 16.8	ns	1.00 ± 0.11	0.89 ± 0.25
	Grasp	ns	82.5 ± 21.3	85.6 ± 15.3	ns	0.89 ± 0.16	0.87 ± 0.20
	Transport	ns	78.8 ± 11.4	70.0 ± 16.1	ns	1.02 ± 0.03	0.97 ± 0.27
	Release	ns	58.0 ± 18.2	67.2 ± 15.1	ns	0.87 ± 0.18	0.90 ± 0.25
2	Reach	ns	92.6 ± 7.4	87.6 ± 11.0	ns	1.01 ± 0.02	1.01 ± 0.26
	Grasp	ns	86.7 ± 13.9	89.2 ± 13.6	ns	0.95 ± 0.10	0.94 ± 0.27
	Transport	ns	79.5 ± 11.9	72.0 ± 9.8	ns	1.01 ± 0.02	1.08 ± 0.08
	Release	ns	82.2 ± 16.7	90.1 ± 8.3	ns	0.94 ± 0.22	1.02 ± 0.06
3	Reach	ns	77.6 ± 15.3	75.3 ± 18.0	ns	1.00 ± 0.07	1.14 ± 0.17
	Grasp	ns	90.4 ± 14.5	92.8 ± 12.3	ns	0.90 ± 0.24	0.97 ± 0.12
	Transport	ns	74.5 ± 10.7	70.0 ± 10.9	ns	1.03 ± 0.05	1.06 ± 0.13
	Release	ns	75.7 ± 15.3	81.3 ± 16.0	ns	0.94 ± 0.15	0.98 ± 0.10
4	Reach	ns	85.3 ± 12.1	71.9 ± 20.6	ns	0.96 ± 0.09	0.84 ± 0.30
	Grasp	ns	78.1 ± 21.9	83.0 ± 21.4	ns	0.83 ± 0.27	0.86 ± 0.23
	Transport	ns	66.2 ± 14.6	65.2 ± 9.7	ns	0.96 ± 0.14	1.00 ± 0.14
	Release	ns	82.5 ± 18.9	86.4 ± 17.2	ns	0.94 ± 0.17	0.95 ± 0.20
		Percent Fixation to Hand Only (%)			Number of Fixations to Hand Only		
Movement	Phase	*p*	Original	Repeated	*p*	Original	Repeated
1	Reach	ns	14.3 ± 6.7	12.0 ± 7.3	ns	0.02 ± 0.04	0.08 ± 0.12
	Transport	ns	8.2 ± 4.8	14.0 ± 9.5	ns	0.52 ± 0.32	0.73 ± 0.47
2	Reach	ns	7.5 ± 4.2	7.5 ± 5.0	ns	0.08 ± 0.09	0.08 ± 0.13
	Transport	ns	10.3 ± 4.0	14.8 ± 6.8	ns	0.58 ± 0.29	0.75 ± 0.34
3	Reach	ns	7.3 ± 4.8	6.3 ± 4.0	ns	0.07 ± 0.17	0.05 ± 0.15
	Transport	ns	11.8 ± 6.1	14.9 ± 6.4	ns	0.74 ± 0.33	0.89 ± 0.32
4	Reach	ns	16.8 ± 12.2	15.8 ± 11.8	ns	0.11 ± 0.18	0.23 ± 0.34
	Transport	ns	13.7 ± 9.6	17.3 ± 4.4	ns	0.68 ± 0.43	0.85 ± 0.33
		Eye Arrival Latency (seconds)			Eye Leaving Latency (seconds)		
Movement	Transition	*p*	Original	Repeated	*p*	Original	Repeated
1	Grasp	ns	0.66 ± 0.16	0.75 ± 0.39	ns	-0.02 ± 0.10	-0.14 ± 0.24
	Release	ns	0.82 ± 0.15	0.90 ± 0.23	ns	-0.15 ± 0.10	-0.30 ± 0.18
2	Grasp	ns	0.73 ± 0.16	0.86 ± 0.35	ns	-0.04 ± 0.10	-0.18 ± 0.23
	Release	ns	0.94 ± 0.12	1.04 ± 0.21	ns	-0.32 ± 0.26	-0.58 ± 0.30
3	Grasp	*	0.93 ± 0.19	1.21 ± 0.36	ns	-0.06 ± 0.18	-0.18 ± 0.16
	Release	*	0.87 ± 0.16	0.98 ± 0.22	*	-0.22 ± 0.11	-0.41 ± 0.19
4	Grasp	ns	0.57 ± 0.10	0.61 ± 0.33	ns	-0.06 ± 0.19	-0.17 ± 0.17
	Release	ns	0.70 ± 0.17	0.82 ± 0.16	ns	-0.34 ± 0.19	-0.53 ± 0.28

3.5. Discussion

Measures that were consistent between the original and repeated studies included all hand velocity, grip aperture, and eye fixation results, along with most peak joint angle and ROM results. Although participants in the repeated study took more time to complete each functional task (greater overall duration), similar relative phase durations between the participant groups indicated that the repeated study participants did not spend a disproportionate amount of time in any one phase.

Participants in the original study may have displayed faster performance due to the prior functional task trials that they completed (that is, during task trials where only motion capture or eye tracking data were captured in the original study). This presumption is likely, given that practice has been shown to decrease functional test completion time [89]. The longer phase durations exhibited by the repeated study participants led to both increased eye arrival latencies and decreased eye leaving latencies. Furthermore, their longer movement times resulted in decreased joint angular velocities in shoulder, elbow, forearm, and wrist DOFs.

Learning effects may have also contributed to discrepancies in hand movement measures between the original and repeated study participants. The repeated study participants exhibited an increased number of movement units and hand trajectory variability, both of which were likely due to the influence of fewer practice opportunities [90], [91]. Furthermore, increased hand trajectory variability presumably contributed to the repeated study participants' increased average hand distance travelled. Hand trajectory variances would be expected to be away from, or in avoidance of, obstacles present in all task movements (box walls and the partition in the Cup Transfer Task, and the shelf frames in the Pasta Box Transfer Task). Future studies that employ GaMA should standardize the amount of functional task practice opportunities that participants receive.

Task demonstration variations by raters may also have contributed to task duration differences between the two participant groups. Although the same script was used to explain the tasks to participants in each study, small variances in task demonstration speed may have been introduced by the raters. Since the timing of demonstrations is known to influence the resulting pace of participants' movements [92], a slower demonstration may have contributed to the repeated study's increase in task duration time. It is recommended that a standard task demonstration video be created and shown to all participants to reduce the possible effects of rater demonstration variation.

The angular kinematic measures revealed offsets in the wrist flexion/extension and ulnar/radial deviation measures of the repeated study participants, likely due to differences in the kinematic calibration pose across the two studies. Such calibration errors are known to be the main limitation of the *Clusters Only* model [45]. In addition, a large standard deviation in trunk flexion/extension was observed for repeated study participants, also attributable to errors in the kinematic calibration. That is, the calibration of this DOF depends on how each participant chooses to 'stand upright'. To limit such deviations in joint angles, the rater must ensure that the participant does not have a bent wrist and is standing as upright as possible, when a kinematic calibration pose is captured.

Further angular kinematics variations were observed between the two participant groups, in both the forearm pronation/supination and wrist radial/ulnar deviation ROMs. Such deviations were introduced by the *Clusters Only* model, which calculates wrist and forearm angles in a manner that is different from other DOFs. This alternative calculation method was chosen because, during the required calibration pose, participants struggled to align their wrist axes of rotation with the global coordinate system, either due to their elbow carrying angle or their inability to supinate their forearm the required amount. As such, the model uses the local coordinate system of each forearm marker plate to calculate wrist and forearm joint angles. Small misplacements of these plates, however, can introduce wrist and forearm joint angle calculation errors. To combat this limitation of the *Clusters Only* model, the rater must take care to align the forearm marker plate with the long axis of the forearm when it is affixed to the participant.

Although little has been done to validate eye tracking and/or motion capture methods in upper limb movement research, many studies have validated motion capture methods for gait measurements [93]. Gait studies commonly revealed that inconsistencies in motion capture marker placement were a large source of anatomical model errors [93]. The *Clusters Only* model used by GaMA attempts to address this issue as it does not require precise individual marker placement, which has been shown to be more reliable than anatomical models [45]; it does, however, introduce its own variability caused by calibration pose inconsistencies. Gait reliability research has also identified intrinsic participant-to-participant variation within a given population and trial-to-trial variation for a given participant [93], [94]. Such variation could similarly explain movement behaviour differences between the original and repeated data sets of this study.

3.5.1. Limitations

Given that this study manipulated numerous experimental factors when comparing the visual and movement measures of two groups of non-disabled participants, it had limitations. It was infeasible for this research to determine the degree to which these factors (different participants, sites, equipment, raters, and task experience opportunities) affected movement measure variation. Additional research on the effects of training could shed more light onto whether or not the amount of practice fully explains the difference in results between the two studies. Although assessment of inter-site/inter-rater reliability of GaMA using the same participant group would also provide valuable information by reducing the effects of inter-participant variability, for this study, a new participant group presented an opportunity to analyze a wider range of normative behaviour; an important consideration when designing a measure meant to be used to characterize functional impairments.

3.5.2. Conclusions

Overall, the results of the repeated study were remarkably similar to those obtained by Valevicius et al. and Lavoie et al. [2]–[4]. Most hand movement, angular joint kinematic, and eye gaze results exhibited by participants in the repeated study were consistent with those observed in the original study. Most significant differences between the results could be explained by the amount of practice that participants in the two studies received, demonstration variations introduced by the rater, and the limitations of the *Clusters Only* kinematics model. Due to its demonstrated reproducibility, it is expected that, in the future, GaMA can serve as a functional assessment tool across different sites and for individuals with sensory-motor impairments in the upper limb.

Chapter 4. Comparing Simulated and Actual Myoelectric Prosthesis Use

The material presented in this chapter is currently being prepared for publication as the article:

H.E. Williams, A.H. Vette, J.S. Hebert, *“Do the movement strategies of non-disabled individuals wearing a simulated prosthesis mimic those of myoelectric device users?”*

The contents of this chapter are identical to the material presented in the manuscript, with the exception of supplementary figures and tables moved into the body of the chapter and text formatting.

4.1. Abstract

Background: Although upper limb prosthetic studies often use simulated prostheses (attached to and operated by individuals with intact limbs), it is not known if these devices elicit the same movement strategies as myoelectric prostheses (operated by individuals with amputation). If movement strategies can be shown to be similar, then the validity of using a simulated prosthesis worn by non-disabled individuals as a proxy for actual prosthesis use can be confirmed.

Objectives: The objectives of this study were to quantify movement strategies exhibited by non-disabled individuals wearing a simulated prosthesis and to compare them to those of individuals with transradial amputation using a myoelectric prosthesis.

Methods: Motion capture was used to obtain hand and upper body kinematics for 12 non-disabled individuals wearing a simulated prosthesis, as they performed a standardized object manipulation task. Performance metrics, end effector movements, and angular kinematics were compared to those of three individuals with transradial amputation who completed the same tasks using their custom-fitted myoelectric prostheses.

Results: Participants using simulated and myoelectric upper limb prostheses performed a standardized object manipulation task with comparable durations, hand velocity peaks, grip aperture profiles, hand distances travelled, hand trajectory variabilities, and ranges of motion for

most joints being studied. Small differences were found in relative phase durations, number of movement units, and some ranges of motion. Findings from this study suggest that simulated myoelectric prosthesis users reach for and pick up objects using comparable movement strategies to those of an actual mid-skilled myoelectric user.

Recommendations: This study supports the notion that non-disabled individuals wearing a simulated prosthesis, perform a standardized object manipulation task using movement strategies that encompass the range of those exhibited by actual prosthesis users. It is recommended that a wider spectrum of myoelectric prosthesis user data be collected to further support this notion and additional research be conducted to determine whether other simulated prosthesis designs provide comparable results.

4.2. Introduction

Upper limb prosthesis use requires an individual to make numerous movement strategy adaptations, that become most apparent when the individual executes tasks that involve object manipulation. In 2005, over 40,000 adults in the United States were reportedly living with an upper limb amputation [95]. Myoelectric prostheses aim to restore or improve impaired arm and hand function [1] so that individuals with amputation can independently accomplish activities of daily living. Despite innovations in prosthetic design and control strategies, the ability to test the usefulness of such advances is limited by the small, heterogenous population of individuals with amputations, each of whom could have different levels of amputation [96], types of prostheses [97], and prosthetic device control experience [98].

For these reasons, researchers studying myoelectric prostheses often use simulated prosthetic devices to assess users' functional control methods. Simulated devices have been used to study control system alternatives [10]–[12], [71], hand-eye coordination [5], feedback systems [13], [14], [74], and compensatory movements [84]. A simulated device allows a non-disabled research participant to activate and control a myoelectric prosthetic hand using their forearm muscles, in a similar manner to an individual with a transradial amputation. Simulated prostheses generally consist of a brace that attaches to the wearer's forearm, with a prosthetic terminal device (hand or hook) extending distally or offset to the dorsal, palmar, or radial side of their hand [99]. The benefit of using simulated devices is that they allow recruitment of a larger number of participants, given the relatively low incidence of individuals with transradial upper limb amputation. A larger number of research participants improves the statistical power of research findings.

It is assumed that non-disabled individuals fitted with simulated myoelectric prostheses will mimic the movement strategies of those who use actual myoelectric prostheses, but this has yet to be confirmed. While previous studies have included both non-disabled participants wearing simulated prostheses and myoelectric prosthesis users, they did not aim to provide a detailed and comprehensive comparison of hand and upper body kinematics between such groups. Amsuess et al. included both types of participants when comparing different device control algorithms, but only examined duration and error measures [69]. Brown et al. used both such participant groups to investigate the effect of sensory feedback, but only analyzed grasping slip measures [75]. Sobuh et al. included both types of participants to study visuomotor behaviour, but only analyzed gaze behaviour and task duration measures [18]. So despite the use of simulated prostheses in research, the inherent assumption that non-disabled individuals can act as movement behaviour substitutes for actual prosthesis users remains untested.

The objective of this study was to compare hand and upper body kinematics of individuals wearing a simulated prosthesis to three myoelectric prosthesis users with transradial amputation, to determine the validity of using non-disabled individuals as a proxy for actual prosthesis use. The same standardized object transfer task was used for kinematic data collection in both the simulated and actual prosthesis participant groups, from which performance metrics, end effector movements, and angular kinematics were derived.

4.3. Methods

4.3.1. Simulated Prosthesis Design

The simulated sensory motor prosthesis, developed by Kuus et al. [100], was used in this study. It was designed to be worn by non-disabled individuals to simulate the function of a myoelectric prosthesis worn by an individual with a right-arm transradial amputation. As shown in Figure 4-1, the simulated prosthesis consists of: a rigid brace to immobilize the user’s wrist and hand; two electrodes (electrode model: 13E200=60 Otto Bock Healthcare Products; Duderstadt, Germany) to read electromyography signals from the user’s forearm muscles; and a myoelectric hand

(MyoHand VariPlus Speed model: 8e38=9-R7 1⁄4 Otto Bock Healthcare Products) mounted underneath the brace, with a slight radial offset to ensure line of sight to the terminal device. The simulated prosthesis wearer controls the device by activating their wrist extensor muscles (to open the hand) and flexor muscles (to close the hand). Although this simulated sensory motor prosthesis was originally designed to investigate the impact of sensory feedback [100], it was used in this study to solely examine motor control.

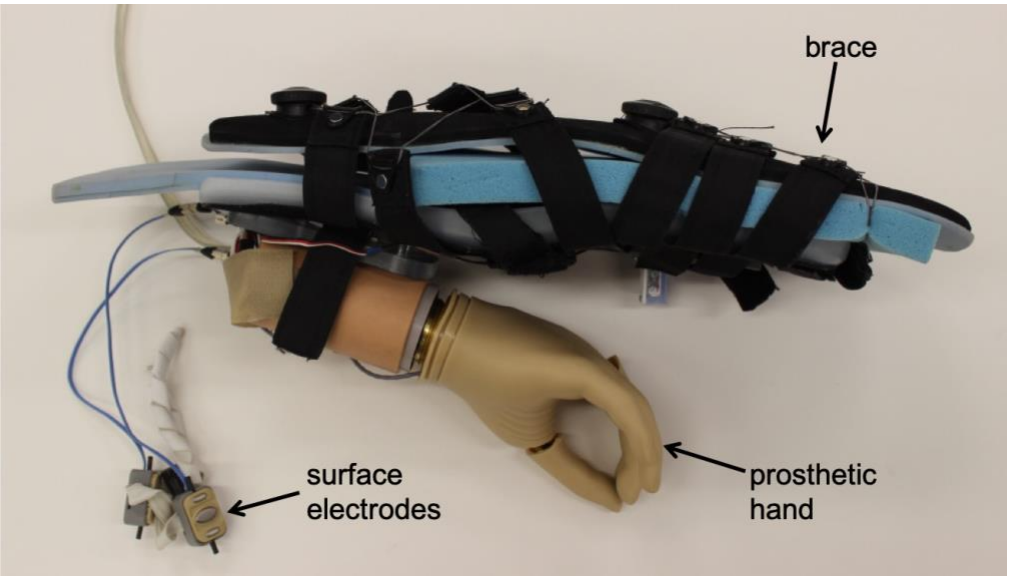

Figure 4-1: The simulated sensory motor prosthesis used in this study, including the hand brace, myoelectric prosthetic hand (mounted below the brace), and surface electrodes.

4.3.2. Participants

A group of 12 non-disabled individuals were recruited to perform a functional task while wearing the simulated prosthesis (hereafter referred to as ‘SP participants’). These individuals had no upper-body pathology or history of neurological or musculoskeletal injuries within the past two years. All SP participants were right-handed, 11 were male, with an average age of 23.8 ± 3.4 years (mean ± standard deviation) and an average height of 176.2 ± 6.2 cm.

Three individuals with transradial amputations were also recruited to perform the same functional task while wearing their usual, custom-fitted myoelectric prosthesis (hereafter referred to as ‘MP participants’ – ‘P1’, ‘P2’, and ‘P3’). Pre-task assessments included AM-ULA and ACMC, administered by a trained occupational therapist, and the Upper Extremity Functional Scale

(UEFS), filled out by the participants. The attributes and assessment scores of the MP participants are shown in Table 4-1.

The study 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).

Table 4-1: Attributes of the MP participants.

	Participants		
Attributes	**P1**	**P2**	**P3**
Age	41	52	37
Gender	F	M	M
Height (cm)	170	184	167
Hand dominance before amputation	Right	Left	N/A (congenital)
Amputation side	Right	Left	Left
Time between amputation and data collection	11 months	18 years	37 years
Hours of prosthesis use per day	10	13	10
AM-ULA score	35	40	33
ACMC score	44.6	59.1	62.0
UEFS score	77.0	63.3	76.2

4.3.3. Functional Task

The Pasta Box Transfer Task, developed by Valevicius et al. [2], mimics the actions of reaching for a kitchen item and moving it to shelves of different heights. In this task, the participant is required to perform the following three movements: *Movement 1* – moving a pasta box from a lower side table immediately to their right (height: 30 inches) to a shelf in front of them (height: 43 inches); *Movement 2* – moving the pasta box to a second shelf at a higher height across the body (height: 48 inches); and *Movement 3* – moving the pasta box back to the starting position on the side table. The participant is required to start each movement with their hand at a 'home' position, and then return their hand to this position at the completion of the task. Each movement, as well as the location of 'home', are depicted in Figure 4-2. Following data collection, each movement can be divided into the phases of 'Reach', 'Grasp', 'Transport', and 'Release', so that discrete characteristics of hand movement can be examined [2]. Note that Figure 4-2 shows the Pasta Box Transfer Task equipment arranged for a right-handed participant; however, the setup was mirrored for participants with a left-side prosthesis.

Figure 4-2: Sequence of the Pasta Box Transfer Task movements (Movements 1, 2, and 3) with the 'home' position labelled. Reach-Grasp and Transport-Release movement segments are colour-coded and illustrated with arrows to show direction. Although the participant in this figure is wearing an eye tracking device, it should be noted that eye gaze behaviour data was not analyzed in this study. Reproduced from Valevicius et al. [2] with permission.

4.3.4. Prosthetic Device Training

Each of the SP participants took part in a two-hour device usage training session. During the session, these participants donned the device, were taught how to control the myoelectric hand using their muscle signals, and were given an opportunity to practice four functional tasks (including the Pasta Box Transfer Task). As the participants carried out these tasks, they were provided with verbal instructions regarding how to improve their control of the device. The participants were allowed to take breaks throughout their training session, as required.

Given that the MP participants were to perform the functional testing with their usual prostheses, they did not require a device usage training session.

4.3.5. SP Participant Experimental Setup

A 12-camera Vicon Bonita motion capture system (Vicon Motion Systems Ltd, Oxford, UK) was used to capture the three-dimensional trajectories of motion capture markers affixed to the SP participants at a sampling frequency of 120 Hz. Three individual motion capture markers were affixed to a rigid surface of the simulated prosthesis, along with additional markers on the simulated hand's index finger (middle phalange) and thumb (distal phalange), as shown in Figure 4-3A. In accordance with Boser et al.'s *Clusters Only* model, rigid plates, each holding four markers, were placed on the back of the simulated prosthesis brace (not used in current analysis) and on the participants' upper arm, trunk, and pelvis [45]. Additional individual markers were placed on the pasta box, shelving unit, and side table, as outlined in the supplementary materials of Valevicius et al. [2].

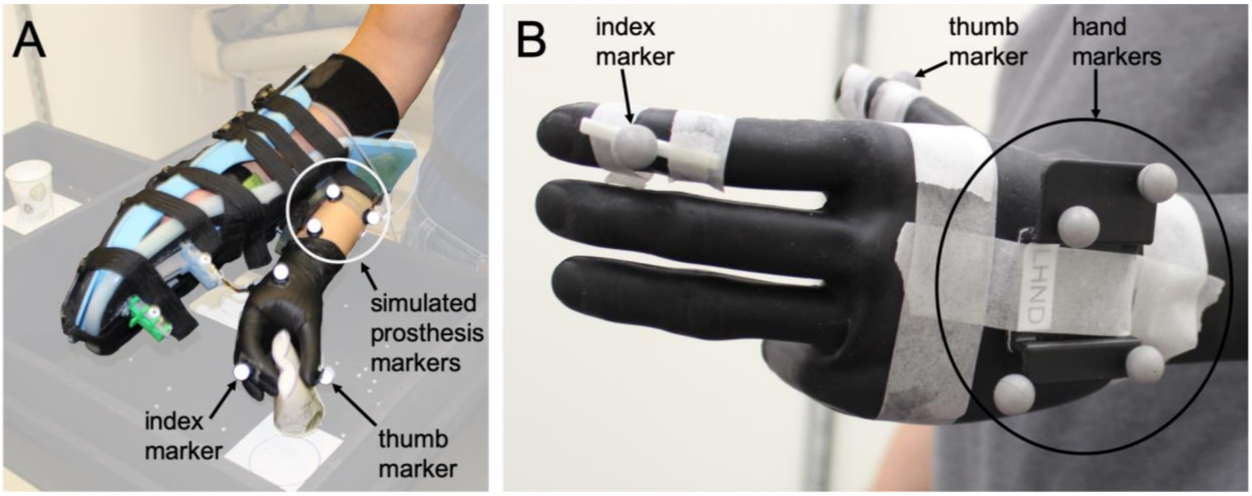

Figure 4-3: Motion capture marker placement on the simulated prosthesis (A), and a myoelectric prosthesis (B).

4.3.6. MP Participant Experimental Setup

An 8-camera Optitrack Flex 13 motion capture system (Natural Point, OR, USA) was used to capture the three-dimensional trajectories of motion capture markers affixed to the MP participants at a sampling frequency of 120 Hz. A rigid plate holding four motion capture markers was affixed to the back of each participant's myoelectric hand, along with individual markers on their index finger and thumb as shown in Figure 4-3B. As with the SP participants, rigid plates holding four markers were placed on the back of the participants' socket (not used in current analysis) and on their upper arm, trunk, and pelvis. Additional individual markers were placed on the task equipment, as outlined in the supplementary materials of Valevicius et al. [2].

4.3.7. Experimental Data Acquisition and Processing

Before each participant performed the functional task, their motion capture calibration pose was collected, as outlined by Boser et al. [45]. Afterwards, each participant was formally introduced to the Pasta Box Transfer Task, which included verbal instructions, a demonstration, and at least one familiarization trial (as the MP participants did not have a device usage training session, they were provided as many practice trials as necessary, until they reported being comfortable with their task performance). Then, with the motion capture equipment recording, trial data were collected as follows.

SP Participants: Each of the twelve participants performed a total of five task trials. If they made an error during a trial, the error was flagged, and that trial's data were discarded. All data from one SP participant were discarded due to poor data quality. Data from a total of 46 trials (from 11 participants) were used in this study.

MP Participants: Due to the varying skill levels of these three participants, each performed a different number of trials: P1 performed 8 trials, with 4 error-free; P2 performed 10 trials, with 4 error-free; and P3 performed 20 trials, with 19 error-free. All error-free trials were used in this study (total of 27 trials across MP participants).

The motion capture data were filtered and segmented into Reach, Grasp, Transport, and Release phases, as outlined by Valevicius et al. [2]. Hand movement measures (for both the simulated and myoelectric prosthetic hands) were calculated using the centre of the hand's three-dimensional position and velocity. Grip aperture was measured as the distance between the index and thumb markers. Angular kinematics of the shoulder and trunk DOFs were calculated, as outlined by Boser et al. [45]. Time-normalized plots of hand velocity and grip aperture were generated, as described by Valevicius et al. [2]. Hand movement measures of peak hand velocity, percent to peak hand velocity, hand distance travelled, hand trajectory variability, and number of movement units (number of velocity peaks) were calculated for each Reach-Grasp and Transport-Release movement segments, as per Valevicius et al. [2]. The duration of each phase and the relative duration of each phase were also calculated. For each task movement (Movements 1, 2, and 3), ROMs were calculated for shoulder and trunk DOFs.

4.3.8. Data Analysis

Given that only three myoelectric prosthesis users were recruited for this study, statistical analyses (analysis of variance, parametric or non-parametric pairwise comparisons, etc.) were not possible. Therefore, these participants were treated as individual case studies and a mean value for each measure was calculated for P1, P2, and P3 (three mean values). Conversely, for the larger population of SP participants, an overall mean value was calculated for each measure. Then, for each measure, the individual P1–P3 mean values were judged as comparable to that of the SP participants only if they fell within 2 standard deviations of the corresponding SP participant mean.

Finally, to further discern possible differences or similarities in the movement strategies exhibited by SP and MP participants in relation to deviation from expected normative movement patterns, the mean values of non-disabled individuals, collected by Valevicius et al. [2], [3], are also presented in this study for comparison.

4.4. Results

The three MP participants were classified by their device control skill level (using the ACMC scores shown in Table 4-1). P1 was considered to be the least-skilled, P2 mid-skilled, and P3 the most-skilled.

4.4.1. Phase Durations

The SP participants had an average overall task duration of 24.5 ± 2.8 seconds, and the three MP participants (P1, P2, and P3) had average overall task durations of 32.7 ± 2.8 seconds, 25.5 ± 4.1 seconds, and 18.8 ± 0.7 seconds, respectively. Baseline non-disabled participants performed this task with an overall duration of 8.8 ± 1.2 seconds. As shown in Figure 4-4 and Table 4-2, the SP participants had comparable phase durations to P2. P1 typically took more time to complete each phase versus the SP participants, whereas P3 took less time (although they still took more time than non-disabled participants). The SP participants also had relative phase durations comparable to P2, whereas P1 and P3 exhibited some differences in relative phase durations, including relatively shorter Grasp and Release phases and relatively longer Reach and Transport phases.

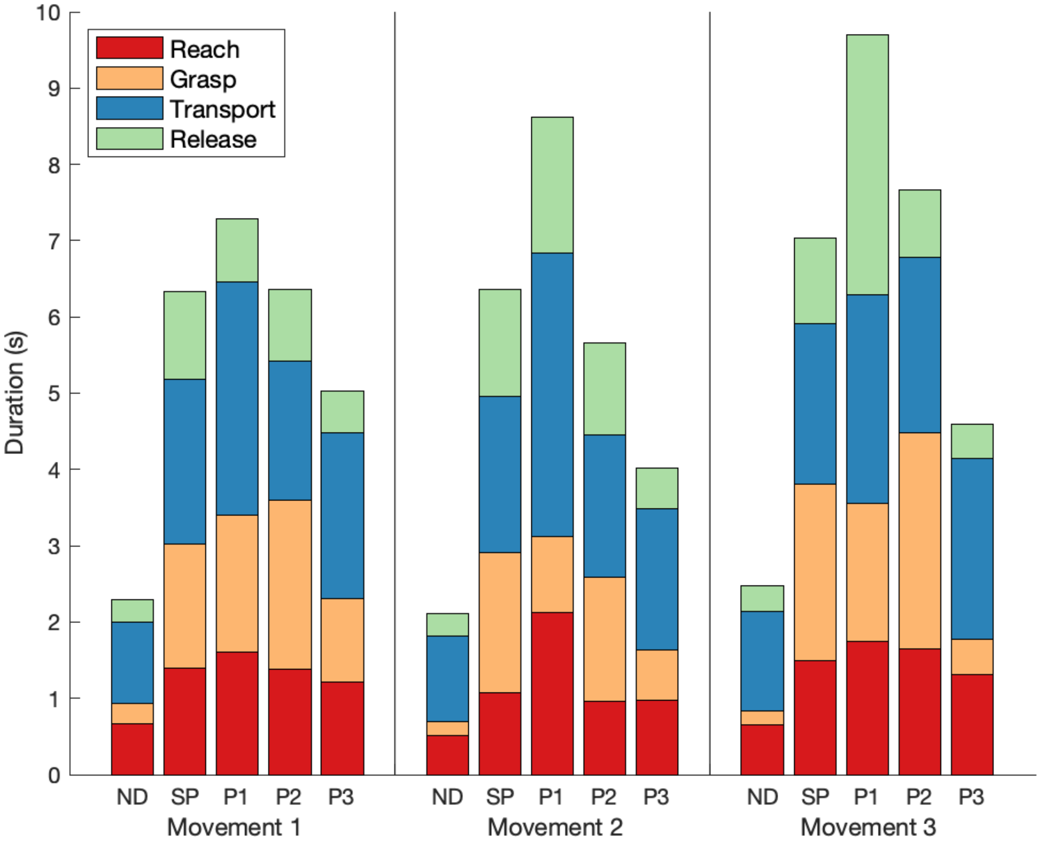

Figure 4-4: Average Pasta Box Transfer Task durations of non-disabled participants ('ND'), SP participants, and the three MP participants (P1, P2, P3). These durations are presented for each movement of the task and are split into Reach, Grasp, Transport, and Release phases and are color coded as per legend.

Table 4-2: Non-disabled (ND) baseline and SP (‘Simulated’) group duration means and across-participant standard deviations, and MP participant (P1, P2, P3) means and standard deviations for each movement (M) and phase (Reach, Grasp, Transport, Release) of the Pasta Box Transfer Task. Table cells that are highlighted indicate that a given mean was outside of two standard deviations of the simulated prosthesis participant group mean (red = higher and blue = lower than the simulated prosthesis participant group).

		Duration (sec)				
		Non-Disabled	Simulated	P1	P2	P3
M 1	Reach	0.66 ± 0.08	1.39 ± 0.28	1.61 ± 0.21	1.39 ± 0.09	1.21 ± 0.11
	Grasp	0.27 ± 0.08	1.63 ± 0.53	1.80 ± 0.21	2.21 ± 0.47	1.10 ± 0.37
	Transport	1.08 ± 0.12	2.15 ± 0.50	3.06 ± 0.62	1.83 ± 0.21	2.17 ± 0.19
	Release	0.28 ± 0.07	1.16 ± 0.43	0.82 ± 0.55	0.94 ± 0.16	0.54 ± 0.15
M 2	Reach	0.52 ± 0.06	1.07 ± 0.17	2.12 ± 0.70	0.96 ± 0.08	0.97 ± 0.09
	Grasp	0.18 ± 0.05	1.84 ± 0.43	1.00 ± 0.40	1.63 ± 0.22	0.67 ± 0.15
	Transport	1.12 ± 0.13	2.05 ± 0.45	3.71 ± 1.45	1.86 ± 0.23	1.84 ± 0.16
	Release	0.30 ± 0.08	1.40 ± 0.61	1.78 ± 0.94	1.21 ± 0.50	0.55 ± 0.08
M 3	Reach	0.65 ± 0.10	1.49 ± 0.35	1.75 ± 0.52	1.64 ± 0.57	1.31 ± 0.10
	Grasp	0.19 ± 0.06	2.32 ± 0.61	1.81 ± 0.28	2.84 ± 2.45	0.46 ± 0.10
	Transport	1.31 ± 0.16	2.10 ± 0.38	2.74 ± 0.24	2.30 ± 0.31	2.36 ± 0.31
	Release	0.34 ± 0.07	1.13 ± 0.55	3.40 ± 0.18	0.87 ± 0.28	0.46 ± 0.28
		Relative Duration (%)				
		Non-Disabled	Simulated	P1	P2	P3
M 1	Reach	29.0 ± 2.0	22.6 ± 4.4	22.0 ± 1.9	22.0 ± 3.3	24.3 ± 2.5
	Grasp	11.5 ± 2.5	25.5 ± 5.9	24.6 ± 1.7	34.4 ± 4.2	21.6 ± 6.0
	Transport	47.1 ± 2.2	34.0 ± 4.0	42.3 ± 9.8	28.7 ± 1.5	43.4 ± 5.0
	Release	12.4 ± 2.3	17.9 ± 3.3	11.1 ± 6.8	14.9 ± 2.6	10.8 ± 3.1
M 2	Reach	24.4 ± 2.0	17.2 ± 2.6	25.0 ± 7.4	17.0 ± 1.1	24.2 ± 2.8
	Grasp	8.3 ± 1.7	28.6 ± 5.7	11.5 ± 2.8	29.1 ± 5.2	16.4 ± 2.7
	Transport	53.0 ± 2.9	32.8 ± 4.9	43.0 ± 11.2	32.8 ± 2.0	45.8 ± 2.6
	Release	14.2 ± 2.7	21.4 ± 6.6	20.6 ± 10.2	21.1 ± 7.7	13.5 ± 1.4
M 3	Reach	26.2 ± 1.8	21.3 ± 3.8	17.9 ± 4.8	22.0 ± 3.5	28.5 ± 1.5
	Grasp	7.4 ± 1.8	32.5 ± 5.3	18.6 ± 2.7	32.9 ± 13.7	10.1 ± 1.7
	Transport	52.9 ± 2.1	30.5 ± 4.5	28.3 ± 3.1	32.3 ± 7.5	51.4 ± 6.1
	Release	13.6 ± 2.2	15.7 ± 5.9	35.2 ± 2.7	12.8 ± 5.9	10.0 ± 5.9

4.4.2. Hand Velocities

Figure 4-5 illustrates that the average hand velocity profile of the SP participants was similar to that of P2 (Figure 4-6 shows the hand velocity profiles of all three MP participants compared to the SP participants). Furthermore, Table 4-3 identifies that the SP participants had peak hand velocities that were comparable to all three MP participants, with the exception that P2 had a greater peak in Movement 1 Reach-Grasp. Table 4-3 also indicates that the SP participants had comparable locations of hand velocity peaks to those of the three MP participants, although P2 had an earlier peak in Movement 1 Reach-Grasp and P3 had generally later peaks.

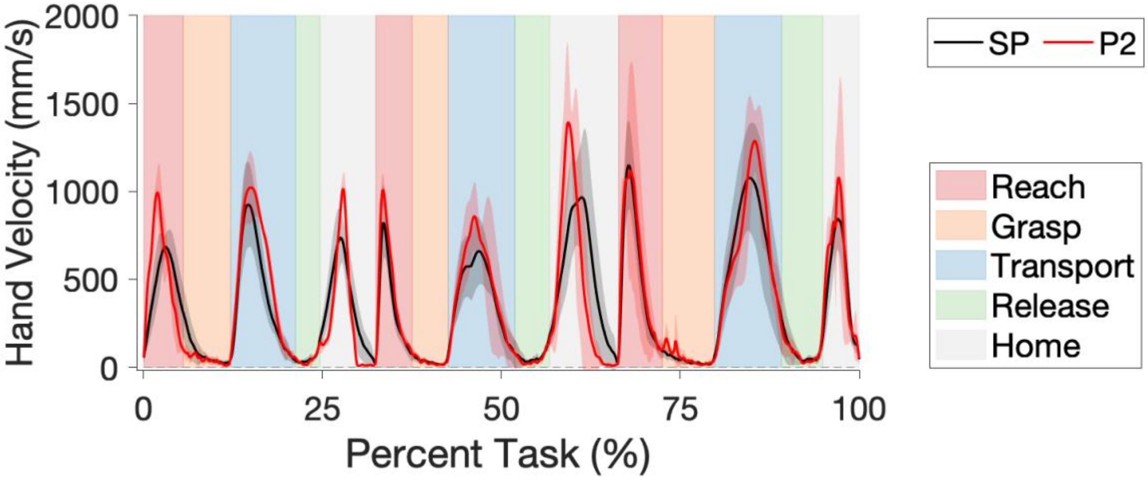

Figure 4-5: Hand velocity profiles of the SP participants (black) and of the MP participant P2 (red). The solid lines represent averages and the shading represents ±1 standard deviation. The average (all SP and MP participants) relative durations of each phase (Reach, Grasp, Transport, Release, Home) of the Pasta Box Transfer Task can be inferred from the width of the corresponding colored bars. Hand velocity profiles were time normalized by phase and resampled using these average relative phase durations.

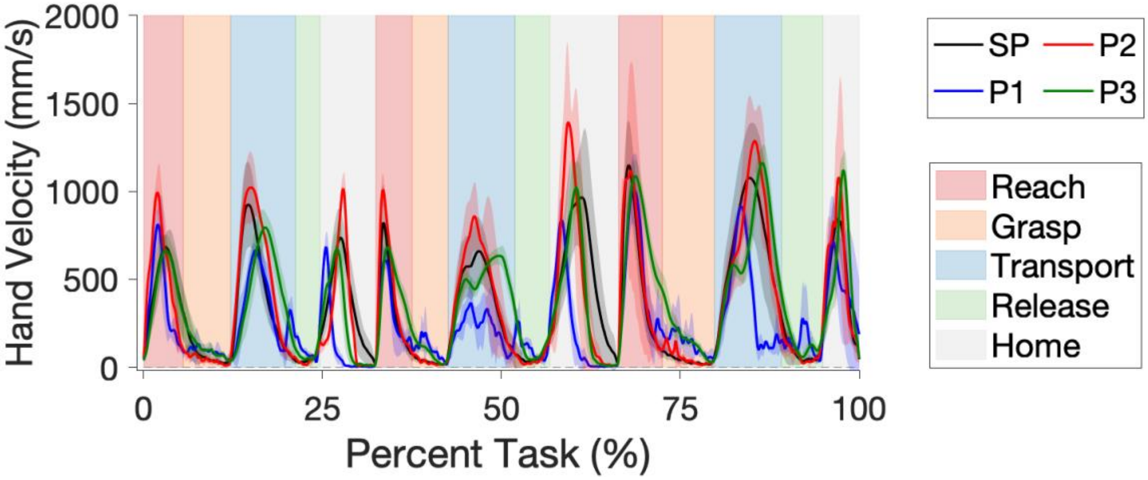

Figure 4-6: Hand velocity profile of the SP participants (black) and of the MP participants (P1: blue, P2: red, P3: green). The solid lines represent averages and the shading represents ±1 standard deviation. The average (all SP and MP participants) relative durations of each phase (Reach, Grasp, Transport, Release, Home) of the Pasta Box Transfer Task can be inferred from the width of the corresponding colored bars. Hand velocity profiles were time normalized by phase and resampled using these average relative phase durations.

Table 4-3: Non-disabled (ND) baseline and SP ('Simulated') group hand movement means and across-participant standard deviations, and MP participant (P1, P2, P3) means and standard deviations for each movement (M) and movement segments (Reach-Grasp: RG; Transport-Release: TRL) of the Pasta Box Transfer Task. Table cells that are highlighted indicate that a given mean was outside of two standard deviations of the simulated prosthesis participant group mean (red = higher and blue = lower than the simulated prosthesis participant group).

		Peak Hand Velocity (mm/s)				
		Non-Disabled	Simulated	P1	P2	P3
M 1	RG	1164 ± 163	812 ± 107	873 ± 117	1038 ± 132	714 ± 61
	TRL	1447 ± 136	1057 ± 188	682 ± 33	1053 ± 179	860 ± 47
M 2	RG	1352 ± 191	927 ± 195	663 ± 32	1018 ± 96	702 ± 62
	TRL	1069 ± 112	779 ± 172	463 ± 64	971 ± 99	661 ± 49
M 3	RG	1666 ± 261	1267 ± 277	1030 ± 199	1389 ± 125	1104 ± 98
	TRL	1598 ± 180	1343 ± 267	931 ± 47	1432 ± 160	1210 ± 87
		Percent-to-Peak Hand Velocity (%)				
		Non-Disabled	Simulated	P1	P2	P3
M 1	RG	41.2 ± 4.5	25.8 ± 4.6	17.7 ± 2.4	16.3 ± 1.7	27.3 ± 5.7
	TRL	29.3 ± 3.1	22.1 ± 5.5	28.4 ± 3.8	22.2 ± 4.4	37.2 ± 5.1
M 2	RG	36.8 ± 4.4	11.9 ± 2.0	14.1 ± 3.8	9.9 ± 0.7	17.0 ± 3.1
	TRL	44.8 ± 8.6	32.5 ± 8.4	36.2 ± 10.2	32.8 ± 7.5	48.5 ± 5.4
M 3	RG	35.5 ± 4.0	11.7 ± 2.4	16.1 ± 2.1	11.4 ± 5.7	18.1 ± 2.0
	TRL	36.2 ± 3.8	35.4 ± 8.6	24.4 ± 1.4	37.8 ± 4.9	44.1 ± 2.7
		Hand Distance Travelled (mm)				
		Non-Disabled	Simulated	P1	P2	P3
M 1	RG	492 ± 26	747 ± 58	745 ± 51	957 ± 31	595 ± 30
	TRL	935 ± 27	1003 ± 42	1043 ± 10	1097 ± 28	912 ± 24
M 2	RG	505 ± 23	545 ± 31	627 ± 138	615 ± 21	428 ± 12
	TRL	802 ± 61	957 ± 70	969 ± 150	977 ± 61	832 ± 30
M 3	RG	746 ± 24	953 ± 77	1075 ± 12	1110 ± 252	748 ± 25
	TRL	1186 ± 31	1407 ± 63	1723 ± 105	1462 ± 22	1324 ± 23
		Hand Trajectory Variability (mm)				
		Non-Disabled	Simulated	P1	P2	P3
M 1	RG	19 ± 5	49 ± 18	32	46	44
	TRL	22 ± 4	72 ± 40	54	44	52
M 2	RG	15 ± 5	38 ± 19	48	18	16
	TRL	20 ± 4	58 ± 48	83	121	15
M 3	RG	19 ± 4	68 ± 29	40	153	23
	TRL	35 ± 8	106 ± 55	79	101	52
		Number of Movement Units				
		Non-Disabled	Simulated	P1	P2	P3
M 1	RG	1.3 ± 0.3	9.8 ± 3.4	8.8 ± 2.4	10.3 ± 3.9	4.7 ± 1.6
	TRL	1.2 ± 0.2	8.4 ± 3.1	6.0 ± 1.4	5.3 ± 1.0	3.8 ± 1.3
M 2	RG	1.0 ± 0.1	11.0 ± 3.7	9.0 ± 1.8	6.8 ± 1.9	3.3 ± 1.0
	TRL	2.3 ± 0.4	11.1 ± 3.6	11.3 ± 6.1	7.5 ± 3.1	4.3 ± 1.2
M 3	RG	1.1 ± 0.1	15.7 ± 4.9	9.3 ± 1.5	15.5 ± 12.2	3.4 ± 1.2
	TRL	1.7 ± 0.4	8.2 ± 3.6	13.0 ± 2.4	5.8 ± 1.3	4.1 ± 0.7

4.4.3. Hand Trajectories

Table 4-3 shows that P1 and P2 had greater hand distances travelled than the SP participants, whereas P3 had smaller hand distances travelled. Table 4-3 also reveals that the hand trajectory variabilities of the SP participants were comparable to those of the three MP participants, with the exception that P2 had larger variability in Movement 3 Reach-Grasp. Finally, Table 4-3 shows that the SP participants had comparable numbers of movement units to P1 and P2, whereas P3 had fewer movement units in each segment, especially in Movement 2 and 3 Reach-Grasps.

4.4.4. Grip Apertures

Figure 4-7 illustrates the average grip aperture profiles of the SP and MP participants, over the course of the Pasta Box Transfer Task. P2's grip aperture profile was most comparable to that of the SP participants, with the exception of the grip aperture magnitudes during Transport phases (P2 grasped the 7-inch × 3.5-inch × 1.5-inch pasta box around the 3.5-inch side to perform the task, rather than the 1.5-inch side, as per the task demonstration). P1's grip aperture profile was also made up of plateaus at hand open or hand closed, although that participant demonstrated early hand opening before the end of the Transport phase (P1 placed the pasta box *close to* the desired targets and then pushed the box to these locations). P3 had a different grip aperture profile compared to the other participants, closing the hand while moving it back to the home location (although still exhibiting small plateaus at hand open).

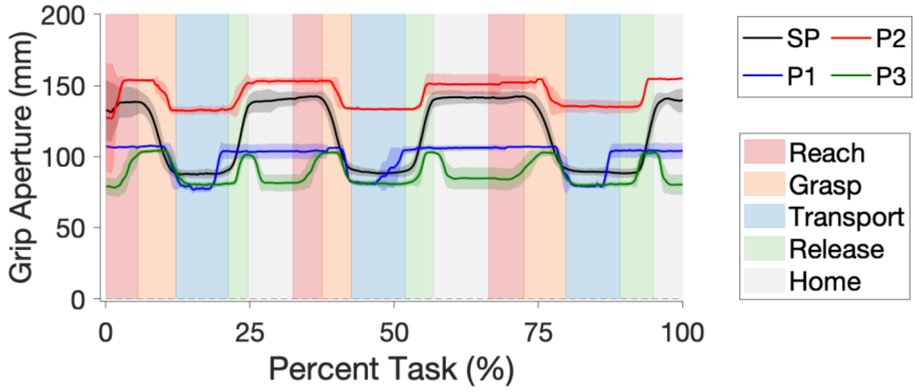

Figure 4-7: Grip aperture profiles of the SP participants (black) and of the MP participants (P1: blue, P2: red, P3: green). The solid lines represent averages and the shading represents ±1 standard deviation. The average (all SP and MP participants) relative durations of each phase (Reach, Grasp, Transport, Release, Home) of the Pasta Box Transfer Task can be inferred from the width of the corresponding colored bars. Hand velocity profiles were time normalized by phase and resampled using these average relative phase durations.

4.4.5. Angular Kinematics

Figure 4-8 illustrates the ROMs of the SP participant group and three MP participants, for all DOFs. P2 had mean ROMs that were comparable to those of the SP participants in all DOFs, except trunk axial rotation (Movements 2 and 3) and shoulder abduction/adduction (Movements 1 and 3). Table 4-4 confirms these findings, as P2's ROMs were outside of two standard deviations of the SP participants' mean for trunk axial rotation in Movement 2 and for shoulder abduction/adduction in Movement 3. Such variations were likely due to the modified grasp used by P2, as previously explained. P1 and P3 had mean ROMs that were within two standard deviations of the SP participants' means, for all movements and DOFs (Table 4-4).

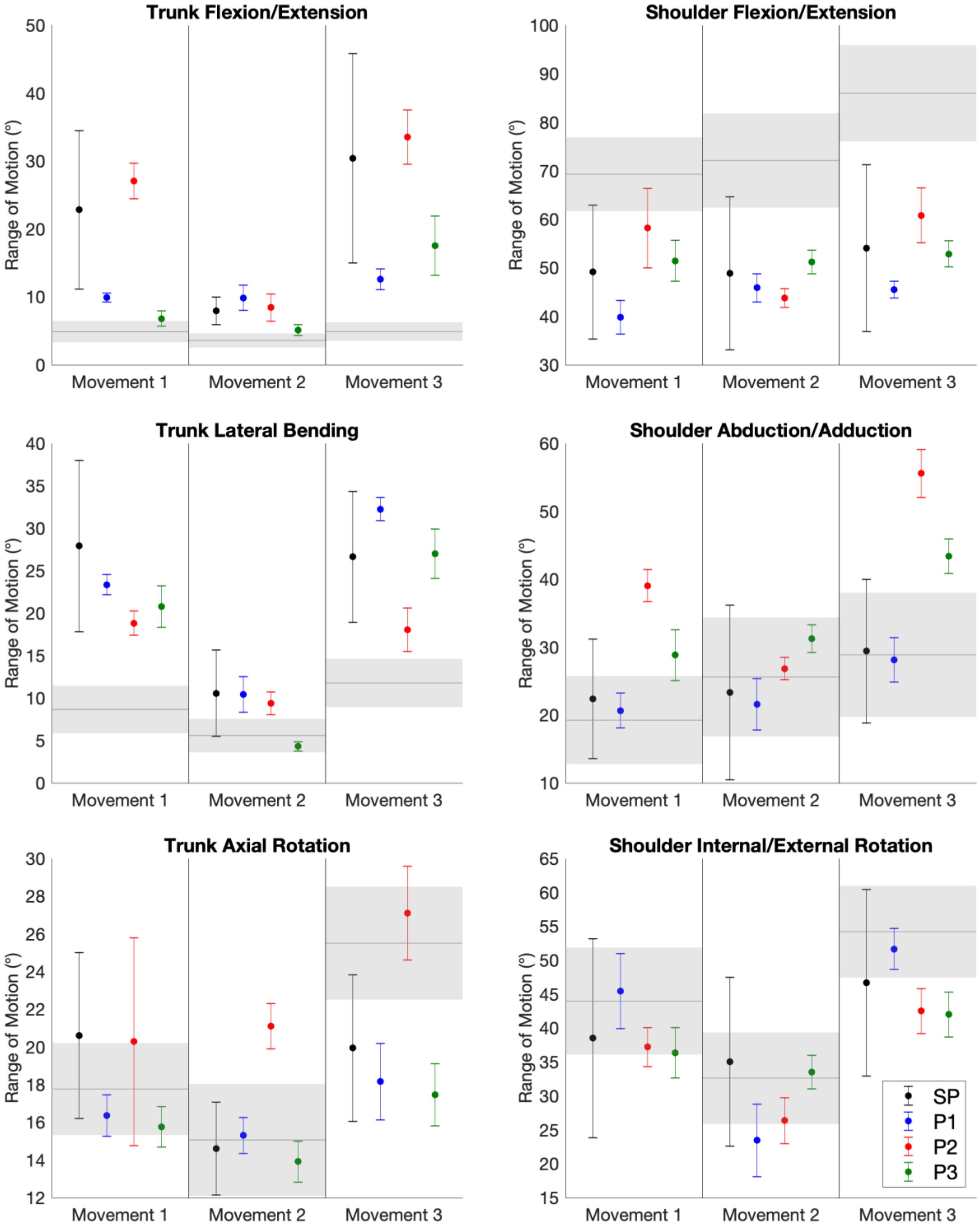

Figure 4-8: Ranges of motion of the SP participants (black) and the MP participants (P1: blue, P2: red, P3: green), for each degree of freedom and each movement of the Pasta Box Transfer Task. Dots indicate the average range of motion for each movement, and each error bar represents ±1 standard deviation. The ranges of motion of a non-disabled baseline are presented with grey lines representing the average and shading representing ±1 standard deviation.

Table 4-4: Non-disabled baseline and SP ('Simulated') group range of motion means and across-participant standard deviations, and MP participant (P1, P2, P3) means and standard deviations for each movement (M) of the Pasta Box Transfer Task. Ranges of motion were calculated for the following degrees of freedom: trunk flexion/extension, lateral bending, and axial rotation; shoulder flexion/extension, abduction/adduction, and internal/external rotation); elbow flexion/extension and forearm pronation/supination; and wrist flexion/extension and radial/ulnar deviation. Table cells that are highlighted indicated that the mean of the myoelectric prosthesis participants was outside of two standard deviations of the simulated prosthesis participant group mean (red = higher than the simulated prosthesis participant group).

		Range of Motion (degrees)				
		Non-Disabled	Simulated	910	963	998
Trunk Flexion/Extension	Movement 1	4.9 ± 1.6	22.8 ± 11.7	9.9 ± 0.7	27.1 ± 2.6	6.8 ± 1.1
	Movement 2	3.6 ± 1.0	8.0 ± 2.0	9.9 ± 1.8	8.4 ± 2.0	5.1 ± 0.8
	Movement 3	4.9 ± 1.4	30.4 ± 15.4	12.6 ± 1.6	33.5 ± 4.0	17.6 ± 4.4
Trunk Lateral Bending	Movement 1	8.7 ± 2.8	27.9 ± 10.1	23.4 ± 1.2	18.8 ± 1.4	20.8 ± 2.4
	Movement 2	5.6 ± 2.0	10.6 ± 5.1	10.4 ± 2.1	9.4 ± 1.3	4.3 ± 0.6
	Movement 3	11.8 ± 2.8	26.6 ± 7.7	32.3 ± 1.4	18.1 ± 2.6	27.0 ± 2.9
Trunk Axial Rotation	Movement 1	17.8 ± 2.4	20.6 ± 4.4	16.4 ± 1.1	20.3 ± 5.5	15.8 ± 1.1
	Movement 2	15.1 ± 3.0	14.6 ± 2.5	15.3 ± 1.0	21.1 ± 1.2	13.9 ± 1.1
	Movement 3	25.5 ± 3.0	19.9 ± 3.9	18.2 ± 2.0	27.1 ± 2.5	17.5 ± 1.6
Shoulder Flexion/Extension	Movement 1	69.3 ± 7.6	49.1 ± 13.8	39.8 ± 3.5	58.2 ± 8.2	51.5 ± 4.2
	Movement 2	72.1 ± 9.7	48.9 ± 15.8	45.9 ± 2.9	43.8 ± 1.9	51.2 ± 2.4
	Movement 3	86.0 ± 9.9	54.1 ± 17.2	45.7 ± 1.5	60.8 ± 5.6	52.9 ± 2.7
Shoulder Abduction/Adduction	Movement 1	19.3 ± 6.5	22.4 ± 8.8	20.7 ± 2.6	39.1 ± 2.3	28.8 ± 3.8
	Movement 2	25.6 ± 8.8	23.4 ± 12.9	21.6 ± 3.7	26.8 ± 1.6	31.2 ± 2.0
	Movement 3	28.9 ± 9.1	29.4 ± 10.6	28.1 ± 3.3	55.6 ± 3.5	43.4 ± 2.6
Shoulder Internal/ External Rotation	Movement 1	44.0 ± 7.9	38.5 ± 14.7	45.4 ± 5.5	37.2 ± 2.9	36.4 ± 3.7
	Movement 2	32.6 ± 6.7	35.0 ± 12.4	23.4 ± 5.4	26.4 ± 3.4	33.5 ± 2.5
	Movement 3	54.2 ± 6.8	46.7 ± 13.8	51.7 ± 3.0	42.5 ± 3.3	42.0 ± 3.3

4.5. Discussion

In this study, twelve participants with unimpaired arm function donned a simulated myoelectric prosthetic device to execute the Pasta Box Transfer Task. Three participants with transradial amputation used their myoelectric prostheses to perform the same functional task and exhibited different levels of device usage proficiency. Overall, comparable movement strategies were observed between the participants.

Phase durations and the relative phase durations of the SP participants resembled those of the mid-skilled MP participant. This is in keeping with Sobuh et al.'s observation that individuals wearing simulated prostheses have functional task performance durations that are similar to the average durations of myoelectric prosthesis users [18]. Furthermore, the SP participants had mean peak hand velocity, percent-to-peak hand velocity, hand distance travelled, and hand trajectory variability values that were close to those of the three MP participants.

The two participant groups exhibited some task performance differences. Although the SP participants' relative phase durations were closest to those of the mid-skilled MP participant, the SP participants had longer Grasp and Release phases than the other two MP participants. Presumably, the Grasp and Release phases were longer because participants using a simulated prosthesis had to mentally focus on device control, to accomplish a seemingly simple manual skill [101]. The MP participants, however, were already familiar with the operational mechanisms of their prostheses, so likely did not have to focus as intently on device control. Furthermore, the SP participants had a slightly increased number of movement units versus the MP participants (especially compared to the expert-skilled MP participant), suggesting that the MP participants possessed slightly better hand function and smoother hand movements. However, both the MP and SP participants all exhibited a larger number of movement units than the non-disabled baseline.

The SP participants had comparable grip aperture profiles to the least- and mid-skilled MP participants, given that all included a series of plateaus. Additionally, all such participants displayed an uncoupling of reach and grasp, consistent with observations reported by other studies of myoelectric prosthesis use [102]. Conversely, the grip aperture profile of the most-skilled MP participant was somewhat similar to that of non-disabled participants [38]. This most-skilled participant closed their hand while moving it back to home (rather than keeping it open) and did not exhibit an uncoupling of reach and grasp. However, this participant still exhibited small plateaus when their hand was fully open.

The SP and MP participants showed comparable joint ROMs. These ROM findings supplement research conducted by Carey et al., which investigated simulated prosthesis angular kinematics [83]. Carey et al. compared the compensatory movements caused by bracing an intact wrist (a simple simulated prosthesis) to those introduced by myoelectric prosthesis use, but observed that a wrist-immobilizing brace did not produce the same magnitude of compensatory movements [83]. In this present study, however, a simulated device has been shown to yield comparable shoulder and trunk ROMs to a myoelectric prosthesis.

Earlier research that employed the Pasta Box Transfer Task compared the hand function metrics of individuals wearing a simulated prosthesis to those of non-disabled participants [9]. The study reported that those wearing the simulated device performed the task slower, with prolonged grasp and release phases, smaller and earlier hand velocity peaks, larger hand distances travelled, increased hand trajectory variability, and more movement units [9]. The results of the present study additionally demonstrate that using a SP results in larger trunk flexion/extension and lateral bending ROMs in comparison to non-disabled individuals, similar to myoelectric prosthesis users. These findings are consistent with prior studies of myoelectric prosthesis users performing different functional tasks [32], [83], [103]. Finally, the SP participants in this present study exhibited smaller shoulder flexion/extension ROMs than non-disabled individuals; again, as previously observed in myoelectric prostheses users [83].

Overall, this study confirms that the hand and upper body kinematics of participants wearing a simulated prosthesis are comparable to those of average transradial myoelectric prosthesis users. However, given that only a small sample of myoelectric prosthesis users were recruited for this research, additional testing should be conducted using a greater number of such participants. Despite the limited sample size, this study did establish that the simulated prosthetic device chosen for this research acts as a good representation of a myoelectric prosthesis. Further research should be conducted to determine whether other prosthetic device designs provide similar or improved representations. Finally, the movement behaviours of the SP participants in this study were presumably comparable to those of a low- to mid-skilled myoelectric prosthesis user, given that the simulated device was only donned for functional testing and practice trials. Presumably, more practice would result in more efficient movement strategies. Research that quantifies performance improvements due to training should be undertaken to both confirm this notion, and to determine the optimal amount of practice trials needed for future SP participants to accurately represent the varied skill levels exhibited by actual prosthesis users.

Chapter 5. Summary of Contributions

The inter-site validation study undertaken by this thesis has demonstrated GaMA to be reproducible, which enhances the feasibility of using GaMA as a quantitative functional assessment tool for individuals with sensory-motor impairment of the upper limb. This work has also shown that GaMA can be successfully used to assess functional movement capabilities of myoelectric prosthesis users who exhibit different skill-levels when using their custom-fitted devices. Furthermore, this research has confirmed that previously collected hand and upper body kinematics of participants wearing a simulated prosthesis (previously collected using GaMA methods [9]) are comparable to those of the average-skilled transradial myoelectric prosthesis user (collected as part of this thesis). Notably, these comparable data sets were collected at two separate research sites equipped with different motion capture and eye tracking technologies, and by different raters – that is, as a research application based on the inter-site reproducibility validation findings from this thesis. As such, it is hoped that all data sets collected during the development, validation, and application of GaMA, can be made available for future comparative analyses across sites.

Gait research already recognizes the benefit of research databases populated by results obtained across sites and technologies [104]. Such databases allow: the burden of data collection to be shared between studies; analyses to be performed with a greater sample population forming a closer representation of the overall population; and examination of an increased number of variables whose influences may be too subtle for statistical analyses otherwise [104]. Given the importance of inter-site comparisons, the work of this thesis advances not only estimations of GaMA, but of the existing data repository of comprehensive movement and eye measures that includes: a normative baseline population [2]–[4], participants with upper limb amputations [67], and those with simulated upper limb impairment (by non-disabled participants) [9].

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Appendix A. GaMA Reproducibility Statistical Analysis

To investigate differences between two groups of research participants (from an earlier research study at a different site, and this present study), a series of repeated-measures analyses of variance (RMANOVAs) and pairwise comparisons were conducted for each measure and task. The designs of the initial RMANOVAs for each measure, which depended on the movement subsets (phases, movement segments, or phase transitions) for which each measure was analyzed, are outlined in Table A-1.

Table A-1: Movement subsets used for analysis of each measure, as well as initial RMANOVA design for each measure.

		Measures					
		Duration & Eye Movement			Hand Movement		Angular Kinematics
		Phase Duration Relative Phase Duration Percent Fixation to Current Number of Fixations to Current	Percent Fixation to Hand Number of Fixations to Hand	Eye Arrival Latency Eye Leaving Latency	Hand Distance Travelled Hand Trajectory Variability Number of Movement Units Peak Hand Velocity Percent to Peak Hand Velocity	Peak Grip Aperture Percent to Peak Grip Aperture Percent to Peak Hand Deceleration	Peak Joint Angles Joint Ranges of Motion Peak Joint Angular Velocities
Movement Subsets	Reach	✓	✓				
	Grasp	✓					
	Transport	✓	✓				
	Release	✓					
	Reach-Grasp				✓	✓	
	Transport-Release				✓		
	End of Grasp			✓			
	Beginning of Release			✓			
	Movements Only						✓
Pasta Box Transfer Task Initial RMANOVA Design (Group × Movement × Movement Subset)		2×3×4	2×3×2	2×3×2	2×3×2	2×3	2×3
Cup Transfer Task Initial RMANOVA Design (Group × Movement × Movement Subset)		2×4×4	2×4×2	2×4×2	2×4×2	2×4	2×4

The measures outlined in Table A-1 were categorized as either: **(1)** measures where the initial RMANOVA had three factors, or **(2)** measures where the initial RMANOVA had two factors. Details of analyses for each category follow, whereby all RMANOVA main effects or interactions were considered to be significant if the Greenhouse-Geisser corrected *p* value was less than 0.05, and all pairwise comparison results were considered to be significant if the Bonferroni corrected *p* value was less than 0.05. Only significant group effects or interactions involving group were further investigated.

Category (1) Measures: If the initial three-factor RMANOVA indicated that a three-way interaction between group, movement, and movement subset was significant, then two-factor RMANOVAs were carried out for each movement subset – with a 2 (group) × 3 (movement) design for the Pasta Box Transfer Task, or a 2 (group) × 4 (movement) design for the Cup Transfer Task. Significant main effects or interactions (involving group) indicated by these two-factor RMANOVAs were followed up with pairwise comparisons between the two groups.

If the initial three-factor RMANOVA did not indicate a significant three-way interaction, two-way interactions between group and movement or movement subset were investigated. If such an interaction was found to be significant, then this interaction was followed up with a collapsed two-factor RMANOVA. Significant main effects or interactions (involving group) indicated by these two-factor RMANOVAs were further investigated using pairwise comparisons between the two groups.

If the initial three-factor RMANOVA did not indicate any significant interactions involving group, but did indicate a group main effect, then pairwise comparisons between the two groups were conducted for each combination of movement and movement subset.

Category (2) Measures: Significant group main effects or interactions between group and movement indicated by the initial RMANOVA were further investigated using pairwise comparisons between the two groups.