Revealing Key Movement Strategies in Upper Limb Function Using a Novel Standardized Kinematic Assessment Tool

By

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Abstract

Introduction: Artificial limbs, also known as prostheses, are used by individuals with upper limb loss to replace some of the functionality of the upper limb. Given the wide range of tasks and movements the upper limbs can accomplish, replacing full functionality can be challenging. While advancements in prosthetic technologies have proven helpful in regaining some functions of the hand, adequately assessing the effectiveness of these devices is critical for further development. A wide range of self-report and performance-based clinical assessments are currently available to evaluate functional capabilities of prosthesis users. However, current clinical assessments are lacking in the ability to quantify how specific prosthetic technologies influence biomechanical movement strategies. Kinematic assessments using motion capture technology could fill this gap by quantifying upper body movement and compensatory strategies in prosthesis users. Selected tasks should mimic those from clinical assessments and challenge the function of prosthesis users through specific task requirements.

Objectives: The overall goal of this thesis was to develop and validate a novel kinematic assessment tool using motion capture technology and two standardized functional tasks in order to characterize movement strategies of non-disabled individuals, and to illustrate the application of this tool in a prosthesis user population, namely transradial body-powered prosthesis users. The specific objectives were to: 1) investigate the consistency and between-session reliability of non-disabled hand movement for the two tasks; 2) quantify normative angular kinematics for the two tasks via peak angle, range of motion, and peak angular velocity measures and assess their between-session reliability; and 3) illustrate the use of the measure in a group of transradial body-powered prosthesis users, to identify key compensatory strategies by comparing upper body joint kinematics to normative values.

Methods: A 12-camera Vicon motion capture system was used to collect three-dimensional marker trajectories at 120 Hz. Twenty non-disabled participants and five transradial body-powered prosthesis users had marker plates with reflective markers attached to upper body segments. Participants completed two standardized functional tasks. The Pasta Box task had participants move a box of pasta to shelves of different heights, and the Cup Transfer task had participants move filled compliant cups over a partition at table-top height. The tasks were divided into discrete movements based on hand velocity and hand trajectory. In non-disabled participants, hand function measures were extracted from three-dimensional hand motion, namely hand distance travelled, hand trajectory variability, peak hand velocity, percent-to-peak hand velocity, number of movement units, peak grip aperture, percent-to-peak grip aperture, and percent-to-peak hand deceleration. In both non-disabled and prosthesis user participants, joint kinematic measures were extracted from three-dimensional joint angles, namely peak angle, range of motion, and peak angular velocity. For all the above measures in the non-disabled data, consistency in task performance was assessed by calculating within-participant variability, and between-session reliability was assessed using the intra-class correlation coefficient. Following non-disabled participant data analysis, the upper body joints' ranges of motion for the body-powered prosthesis users were compared to those of the non-disabled individuals to identify any compensatory movements employed by prosthesis users to complete the task.

Results: The two standardized functional tasks elicited consistent kinematic strategies within a non-disabled population, with good between-session reliability. Cross-body movements in the

Pasta Box task caused an earlier occurrence of hand velocity peaks, and movements requiring clearing an obstacle while transporting an object displayed double hand velocity peaks and longer deceleration phases. Both tasks required minimal trunk motion. Cross-body movements and reaches to objects further away required greater range of motion at the trunk and at the elbow joint. In prosthesis users, compensatory strategies were identified mainly at the trunk. While no significant shoulder compensations were observed in prosthesis users, some reduction in shoulder flexion/extension occurred, likely due to the restrictive nature of the harness required to operate a body-powered prosthesis.

Discussion: This work successfully developed a novel kinematic assessment and validated its use in a non-disabled population by reporting on hand function and angular kinematic strategies for two standardized functional tasks. The use of this assessment was illustrated in a prosthesis user population, where the tasks challenged key areas of prosthesis use, identifying compensatory strategies at the trunk. This assessment has created a foundation for the quantitative assessment of prosthesis users of various prosthetic technologies and levels of amputation.

Preface

This thesis is an original work by Aïda M. Valevicius. The research project, of which this thesis is a part, received research ethics approval from the University of Alberta Research Ethics Board, "Functional metrics for humans with bi-directionally integrated prosthetic limbs", Pro00054011, the Department of the Navy Human Research Protection Program (DON-HRPP), and the SSC-Pacific Human Research Protection Office (SSCPAC HRPO).

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Glossary of Symbols and Terms

<: Less than

>: Greater than

%: Percent

3D: Three-dimensional

ACMC: Assessment of Capacity of Myoelectric Control

AM-ULA: Activities Measure for Upper Limb Amputees

ANOVA: Analysis of Variance

cm: Centimeter

CMC: Coefficient of Multiple Correlation

DASH: Disabilities of the Arm, Shoulder, and Hand

DoF: Degree of freedom

EMG: Electromyography

HAT: Hand Assessment Tool

Hz: Hertz

ICC: Intra-class correlation

ISB: International Society of Biomechanics

JTHF: Jebsen-Taylor Test of Hand Function

LCS: Local coordinate system

MDC: Minimal detectable change

mm: Millimeter

MPL: Modular Prosthetic Limb

Mvmt: Movement

n: Number

NR: Not reported

PTA: Point of task achievement

PULTSE: Pediatric Upper Limb Temporal-Spatial Equation

RG: Reach-Grasp

sec: Seconds

SD: Standard deviation

SEM: Standard error of measurement

SHAP: Southampton Hand Assessment Procedure

TMR: Targeted muscle reinnervation

TR: Transport-Release

UEFS: Upper Extremity Functional Scale

WPV: Within-participant variability

Chapter 1. Introduction

1.1 Problem Definition

Several types of artificial limbs, also known as prostheses, are available for individuals who have suffered upper limb loss. Functional prostheses, such as body-powered and myoelectric prostheses, attempt to replace some of the lost function at the upper limb (Jette, 2017). However, difficulties in reaching and grasping objects often remain, which disrupts natural movement at more proximal joints and body segments, namely the elbow, shoulder, and trunk (Klein et al., 2011). When natural movement is disrupted in prosthesis users, compensatory strategies, as revealed through an increase in range of motion (RoM), are routinely observed at the trunk (Carey et al., 2008; Hussaini et al., 2017; Major et al., 2014; Metzger et al., 2012) and shoulder (Bertels et al., 2009; Major et al., 2014; Metzger et al., 2012). Increased use of more proximal joints, the trunk, or even the sound limb can increase the risk of sustaining an overuse injury (Burger and Vidmar, 2016; Gambrell, 2008; Jayakumar et al., 2017; Ostlie et al., 2011a). Musculoskeletal pain is frequent in prosthesis users: shoulder pain was reported at a rate of 44.3 and 50 %, and lower back pain was reported at a rate of 76.6 and 100% in individuals with a unilateral and bilateral amputation, respectively (Ostlie et al., 2011a). Pain is also reported for both the affected and sound limb (Datta et al., 2004).

Advancements in prosthetic technologies attempt to mitigate some of the risks of sustaining overuse injuries by incorporating components that allow for more natural arm movement (Cowley et al., 2016). The effectiveness of new prosthetic components in reducing these compensatory movements has not been well quantified. Many clinical assessments evaluate quality of motion, or how a movement is performed, using scoring criteria, but they do not precisely quantify specific compensatory strategies, given that scoring is often observer-based and subjective (Wang et al., 2018). Hence, there is a need for assessment tools that can quantify changes in function, performance, and movement patterns in prosthesis users (Wang et al., 2018).

Kinematic assessment using motion capture technology, an excellent tool for tracking limb movement for a variety of conditions and tasks, could fill this gap (Valevicius et al., 2018b). Both gross upper limb movement and finite dextrous finger movement can be extracted from motion capture data. Moreover, motion capture technology allows for a variety of tasks to be used, as long as they are standardized and repeatable (Kim et al., 2014). Unfortunately, there are few comprehensive protocols available for measuring upper limb prosthetic movement with motion capture technology that incorporate complex and challenging tasks for prosthesis users that mirror those used in clinical assessments. There is currently a need for such an assessment as new technological advancements are integrated into prosthetic devices. Quantifying both non-disabled and prosthesis user movement can provide a comprehensive understanding of how prosthetic device components affect prosthesis user movement (Gambrell, 2008). Identifying clear compensatory strategies can empirically inform clinicians regarding intervention procedures, hopefully reducing the incidence of musculoskeletal complications in prosthesis users.

1.2 Thesis Objectives

The overall goal of this thesis was to develop and validate a novel kinematic assessment tool using motion capture technology and two standardized tasks in order to characterize movement strategies of non-disabled individuals and one prosthesis user population, namely transradial body-powered prosthesis users. The specific objectives were to: 1) quantify non-disabled hand movement for the two standardized functional tasks based on hand trajectory, hand velocity, and grip aperture measures and investigate the consistency and between-session reliability of these measures; 2) quantify normative angular kinematics for the two tasks via peak angle, RoM, and peak angular velocity measures and assess the consistency and between-session reliability of these measures; and 3) use the two tasks as an illustration of the utility of the measure and application of this novel technique in transradial body-powered prosthesis users by identifying key compensatory strategies through the comparison of upper body joint kinematics to non-disabled values.

1.3 Chapter Summary

<u>Chapter 2: Review of Prosthetic Technologies and Prosthesis User Assessments</u>

Chapter 2 provides an overview of the background literature on the topics that motivated this thesis. It begins with a summary of the types of prostheses available to individuals who have suffered upper limb loss. It then reviews the wide range of clinical assessment tools, either self-report or performance-based, that are available to clinicians for monitoring the functional status of prosthesis users. The gap created by the clinical assessments, namely the need to quantify compensatory movements strategies, is highlighted. Accordingly, the final part of the chapter reviews the current use of kinematic assessments in prosthesis user populations, emphasizing the lack of standardization among protocols and the underrepresentation of studying body-powered prosthesis users.

<u>Chapter 3: Review of Upper Body Kinematic Protocols for Non-Disabled Populations Using Optical Motion Capture Technology</u>

Prior to investigating populations with impairments, it is critical to have a thorough understanding of non-disabled behaviour; therefore, Chapter 3 covers, in depth, the state of the literature on the use of motion capture technology in non-disabled populations for studying kinematics at the upper body. This chapter presents information on kinematic model characteristics, performed functional tasks, and kinematic outcomes used in the literature. It also examines whether kinematic protocols were assessed for validity and reliability.

<u>Chapter 4: Characterization of Normative Hand Movements During Two Functional Upper Limb Tasks</u>

Chapter 4 introduces the two standardized functional tasks developed for our novel kinematic assessment tool, as well as the data collection procedure. Non-disabled hand function was quantified in terms of task completion time, hand trajectory, hand velocity, and grip aperture. Through an analysis of within-participant variability, non-disabled hand function was shown to be consistent. Furthermore, a between-session reliability assessment revealed non-disabled hand function to be reliable.

Chapter 5: Characterization of Normative Angular Joint Kinematics During Two Functional Upper Limb Tasks

Chapter 5 builds on Chapter 4 and reports results for angular joint kinematics at the trunk, shoulder, elbow, and wrist joint for all three planes of movement and for both functional standardized tasks. Measures extracted from the kinematics time series included peak angle, RoM, and peak angular velocity. Through an analysis of within-participant variability, non-disabled angular joint kinematic measures were shown to be consistent. Furthermore, a between-session reliability assessment revealed that non-disabled angular joint kinematic measures are reliable.

Chapter 6: Compensatory Strategies of Body-Powered Prosthesis Users Reveal Primary Reliance on Trunk Motion and Relation to Skill Level

Chapter 6 introduces how our novel kinematic assessment can be used in a population of transradial body-powered prosthesis users. Prosthesis user RoM results were compared to non-disabled RoM results for both functional tasks. Compensatory strategies were identified mainly at the trunk. In addition to quantifying compensation, prosthesis user RoM results were correlated with the AM-ULA to investigate whether there was an association between functional movement and skill level. Prosthesis users with a higher skill level, indicated by a higher AM-ULA score, displayed trunk and shoulder flexion/extension RoM values closer to non-disabled values.

Chapter 7: Conclusions and Future Directions

Chapter 7 includes concluding remarks about the potential use of standardized kinematic assessments in the performance evaluation of prosthesis users, and possible future applications to evaluate advancements in prosthetic technologies and therapeutic interventions.

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Chapter 2. Prosthetic Technologies and Prosthesis User Assessments

2.1 Chapter Preface

This chapter provides important background information for the subsequent chapters in this thesis. The chapter begins by giving an overview of current types of prosthetic devices available for individuals who have suffered upper limb loss and is followed by an explanation of prosthesis rejection. The incidence of musculoskeletal injuries in prosthesis users is discussed, highlighting the importance of technological development in an attempt to mitigate pain and injury, and of proper identification of movement strategies and functional capabilities in prosthesis users. This topic segues into the latter part of the chapter, which covers assessment tools used to evaluate the functional capabilities of prosthesis users. The first group of assessments discussed are clinical assessments, including self-report and performance-based assessments. Following those, laboratory assessments, more specifically kinematic assessments, currently available are presented, and insights into the current state of the literature regarding kinematic assessments used for upper limb prosthesis users are provided.

2.2 Prosthetic Technologies

Living with an upper limb amputation usually causes significant activity limitations. Upper limb prostheses are available to aid in restoring function, but replacing the functionality of the upper limb is challenging. The upper limbs allow for a wide range of gross and fine motor function and the successful completion of a variety of very complex tasks (Jette, 2017). Different types of prostheses are available for people who have suffered an upper limb amputation, typically categorized as passive prostheses and functional prostheses, including myoelectric and body-powered prostheses. The typical function of passive prostheses is to restore a natural arm appearance and symmetry. They may provide a certain level of functionality by aiding in bimanual tasks through stabilizing objects. They are also the lightest of all three types of devices since they do not require complex mechanical systems or motors (Jette, 2017). Myoelectric prostheses are controlled via electrodes placed in the socked that read electromyographic (EMG) signals from residual muscles (Chadwell et al., 2016; Marasco et al., 2015; Pilarski and Hebert, 2017). For most transradial amputations, the muscle activations used for opening and closing the hand are similar to those for opening and closing the natural hand; therefore, control of the myoelectric device can be physiologically natural (Uellendahl, 2017). Typically, extensor muscles native to releasing a grasp will be used for opening the hand, and flexor muscles will be used for closing the hand (Uellendahl, 2017). An advantage of some myoelectric prostheses, especially transradial prostheses, is the lack of a harness and a self-suspending mechanism, therefore increasing comfort and ease of donning and doffing (Uellendahl, 2017). There are some drawbacks to myoelectric prostheses. They are currently not suitable for all environments, especially not for wet and dirty environments, or areas with electronic interference. Interference with the electrodes in the socket may cause inconsistent signals and unintended actions to take place or signals to be unavailable. Interference occurs due to socket slippage or if the electrodes lose contact with the skin (Uellendahl, 2017). Myoelectric prostheses may become difficult to control for more proximal levels of amputation due to the need to control several degrees of freedom (DoFs), which complicates the operation of the device. Given that Objective 3 within the overall goal of this work is to illustrate the use of a kinematic assessment in body-powered prosthesis users, the functional capabilities of body-powered prostheses will be discussed in further detail below.

2.2.1 Body-Powered Prostheses

Body-powered prostheses have been available since the middle of the 20th century without any significant design changes in the last 50 years (Hashim et al., 2018). Body-powered prostheses' key components are a prosthetic socket, prosthetic liner, harnessing, control cable and terminal device. Their mechanism of use is simple, where certain body movements, mainly at the shoulder and shoulder girdle in the form of shoulder flexion and biscapular abduction, are required to voluntarily open or close the terminal device. Body movement create tension in the control cable, which is attached to a harness worn around the users' shoulders (Hashim et al., 2018). Some body-powered prostheses users may opt for a hand terminal device instead of a hook (Smit et al., 2012), giving it a more cosmetic look. Body-powered prostheses are commonly used as they are quiet to use, of moderate cost, reliable, durable, and provide some level of sensory feedback about the positioning of the terminal device. Proprioceptive feedback is offered through variable tension in the cable and harness system, offering the user some information about the force, position, and velocity of the prosthetic terminal device (Plettenburg, 2002). Moreover, body-powered prostheses are very functional in a variety of environments. They are appropriate for heavy-duty work in wet, dirty, and corrosive environments since they are less prone to damage (Uellendahl, 2017). As another advantage, body-powered prostheses require less training and adjustments than myoelectric prostheses (Carey et al., 2015).

Although body-powered prostheses are commonly used, they do have some shortcomings. One of the main drawbacks with body-powered prostheses is the harness required to operate the prosthesis and corresponding body movements. This harness can often cause discomfort and pain since large forces are required to open the terminal device (Uellendahl, 2017). In addition to having sufficient strength to open the device, a sufficient amount of RoM is required for adequate cable excursion (approximately two inches), especially for tasks requiring above head movement (Jette, 2017). Therefore, often increased movement is present at the impaired limb (Doeringer and Hogan, 1995). Compensatory movements and high forces required to constantly open the terminal device may lead to overuse injuries over time, which is a concern with body-powered prostheses (Doeringer and Hogan, 1995; Metzger et al., 2012). New materials and mechanical alterations have been put into place to try and improve these prosthetic devices, with the main goal being improving efficiency of the prosthetic device (Hashim et al., 2018).

2.2.2 Prosthesis Rejection

Improvements in prostheses are ongoing in an attempt to address the areas of concern reported by prosthesis users. Determining what areas of development are most valued by prosthesis users is key since, if a prosthetic device does not fulfill a user's requirements, or if the fit and comfort are not optimal (Jette, 2017), there is a chance that the device may be rejected. In a pediatric population, passive hands are rejected at a rate of 61%, which is significantly higher than functional prostheses, more specifically body-powered hook devices, which are rejected at a rate of 48% (Biddiss et al., 2007). In an adult population, body-powered hands have been reported to be rejected at a rate of up to 65%, which is significantly higher than the rejection rate of electric hands (41%), body-powered hooks (51%), or passive hands (47%) (Biddiss et al., 2007). Moreover, it was found that a third of prosthesis users are unsatisfied with the functionality of their device for activities of daily living (ADL) or work (Datta et al., 2004).

2.2.3 Prevalence of Musculoskeletal Injuries

Individuals with acquired or congenital upper limb loss report an incidence of overuse problems at a rate greater than non-disabled individuals (Burger and Vidmar, 2016; Ostlie et al., 2011a). Pain typically occurs at more proximal joints, such as the shoulder (Burger and Vidmar, 2016), but can also occur at the contralateral side for the elbow and wrist (Datta et al., 2004). A study by Datta et al. reported an incidence of shoulder pain of 45% among their 80 participants (Datta et al., 2004), whereas Ostlie et al. reported an even higher incidence of 59% (Ostlie et al., 2011a). An earlier study of overuse injuries in individuals with an amputation revealed that problems in the sound limb were reported by 50% of individuals (Jones and Davidson, 1999). Since this initial study, more specific rates of pain at the elbow and wrist in the sound limb have been reported. Burger and Vidmar, Datta et al., and Ostlie et al. all reported rates of pain at the elbow, wrist, and hand above 20%, reaching up to 43% (Burger and Vidmar, 2016; Datta et al., 2004; Ostlie et al., 2011a). In addition to limb pain, both upper and lower back pain is reported in the literature. Datta et al. showed that 40% of their participants reported upper back pain (Datta et al., 2004) and Ostlie et al. reported a slightly higher incidence, where upper back pain and lower back pain were reported in 57 and 45.3% of participants, respectively (Ostlie et al., 2011a). The increased rates of pain and overuse injury observed in individuals with upper limb loss are likely due to the aberrant motions, often termed compensations, observed at more proximal joints and the sound limb (Gambrell, 2008). The limited function of current prosthetic devices may cause some of the aberrant movement to occur (Highsmith et al., 2009; Silcox et al., 1993).

2.2.4 Prosthesis Development

Evidenced by the high rejection rates and rates of pain and overuse injury, prosthesis users are often unsatisfied with the devices that are available to them. Both body-powered and myoelectric prostheses have shortcomings that need to be addressed through prosthesis development. Body-powered prosthesis users would like to see improvements in both tactile and proprioceptive sensory feedback (Biddiss et al., 2007). Myoelectric users would like to see increased dexterity, reduced frequency of unplanned movements, and sensory feedback. They are also looking for better shoulder and elbow control, as otherwise the device is deemed more of a hindrance than help. Independent movement capacity for fingers, wrist, elbow, and shoulder was also a desired feature for myoelectric users (Biddiss et al., 2007). Moving forward, greater advancements in sensory feedback through nerve and brain interfaces were of interest to prosthesis users in addition to availability of lighter and more durable materials and better battery technology (Biddiss et al., 2007). These prosthesis user requests highlight how continued development is necessary to create more comfortable and functional prostheses, especially for individuals with a high level of amputation or bilateral amputation based on users' requirements (Biddiss and Chau, 2007)

Research is ongoing to create technologies that incorporate sensory feedback, multi-articulated joints, and more reliable control strategies. Some advances have been made, such as the DEKA prosthetic arm, which provides movement capabilities that are superior to traditional myoelectric prostheses (Resnik et al., 2014). The Modular Prosthetic Limb (MPL), a prosthesis with 26 DoFs and developed at the Applied Physics Laboratory (APL), Johns Hopkins University (Johannes et al., 2011), and a 21 DoF prosthesis, the Vanderbilt Multigrasp prosthesis (Dalley et al., 2011), are examples of novel prosthetic devices that are attempting to incorporate a greater number of DoFs to mimic the movements of a natural arm. Ideally, the inclusion of a greater number of DoFs into prosthetic devices will have a direct effect on movement mechanics of the user. Even small changes in the prosthetic limb can have effects on whole body movement (Bertels et al., 2009). In addition to better terminal devices, better control mechanisms are being developed either through interfaces involving muscle, the central nervous system, or peripheral nerves (Hutchinson, 2014). Targeted muscle reinnervation (TMR) surgery has been beneficial in improving control of prosthetic arms as residual median, ulnar, radial, musculocutaneous nerves can be reinnervated to remaining muscles in the residual limb to create more control sites (Dumanian et al., 2009; Kuiken et al., 2004). The use of new techniques and devices mimicking a more natural arm is hoped to lead to movement strategies that are closer to non-disabled movement, therefore reducing the incidence of pain and overuse injuries.

Based on the knowledge we have about prosthesis use, prosthesis rejection rates, incidence of musculoskeletal pain and injury, and prosthesis improvements desired by users, advancements in prosthetic technologies need to be ongoing. Given that not all advancements in prosthetic technologies may actually benefit the user, it is important to assess how novel devices and components impact prosthesis user functional movement and performance. Therefore, assessments need to be sensitive enough to quantify functional movement and performance of standard of care prostheses, in order to investigate if new technology actually causes a significant enhancement to prosthesis user function.

2.3 Clinical Assessment

2.3.1 Prosthesis User Clinical Assessments

With the advancement of prosthetic technologies, clinicians need validated and reliable measures to assess the function and performance of prosthesis users (Hill et al., 2009; Lindner et al., 2010). Several validated measures developed for use in prosthesis user populations are available (Wright, 2006). These clinical assessments or measures used to evaluate upper-limb prosthesis use typically fall into two categories: 1) self-report measures, and 2) performance-based measures (Resnik et al., 2017). Self-report measures typically focus on asking questions about the ability to complete self-care and daily activities, pain, quality of life, and a patient's perception of experiences (Wang et al., 2018). Self-report measures are easy to administer and can be administered to a large number of individuals at once; however, they are subject to recall and response bias (Prince et al., 2008). Performance-based measures may include speed-based or observational rater-based assessments. Performance-based measures can provide independent and reproducible assessments of the ability to perform ADLs (Wang et al., 2018).

2.3.1.1 Self-Report Measures

Self-report measures are a fast and accessible way to gather information on the functional capabilities of prosthesis users. Their cost of administration is typically low and the burden set on both the researcher or clinician and patient low (Dishman et al., 2001). Questionnaires are easy to administer either to a large amount of people at one time point or to one individual over several time points throughout their rehabilitation process. Self-report questionnaires allow for insight into an individual's capability of completing ADLs, experiences of pain and discomfort, and satisfaction (Wang et al., 2018). They may, however, produce skewed results given they rely on individuals properly recalling events. Self-report measures can often contain recall and response bias, where the participant might have trouble remembering specific events or alter their answers based on social desirability (Prince et al., 2008). Two common self-report measures used to assess function in upper limb prosthesis users are presented below.

Disabilities of the Arm, Shoulder, and Hand (DASH)

The DASH is a self-report test designed to assess the functional status, mainly physical function, of populations with upper limb musculoskeletal impairments (Hudak et al., 1996). It is a commonly used questionnaire in the field of upper limb prosthesis use (Resnik et al., 2017). The DASH questionnaire asks questions about symptoms (i.e., pain, weakness, and stiffness) and functional status (i.e., physical, social, and psychological). Key activities evaluated within the functional status section include, but are not limited to, house/yard chores, recreational activities, eating, sports, and family care (Hudak et al., 1996). The questionnaire asks individuals to rate the difficulty of completing the activities mentioned above on a 5-point scale, 1 indicating no difficulty and 5 being unable to complete the task. The scores are summed, and the score is transformed to range from 1 to 100, with a greater score indicating greater disability. The DASH has been validated to use in populations with both limb trauma or amputation (Davidson, 2009). A disadvantage of the DASH is that it does not take into account which arm is used to measure the functional capacity of an individual. Therefore, no information is available regarding if the limitations are related to the prosthetic or natural arm (Ostlie et al., 2011b).

Upper Extremity Functional Scale (UEFS)

The UEFS is a measure of functional activity that was developed for adult individuals living with an amputation (Burger et al., 2008; Van Gils et al., 2013). Many modified versions of the UEFS have been used in populations using various prosthetic devices (Burger et al., 2008; Jarl et al., 2012; Resnik and Borgia, 2012) as well as orthotic devices for the upper limb (Jarl et al., 2012). The UEFS is derived from the Orthotic and Prosthetics User Survey (OPUS) (Heinemann et al., 2003) and is a self-reported 23-item questionnaire. The activities evaluated in the UEFS include activities of self-care such as washing, tying shoelaces, and dressing, to eating, writing, and donning and doffing a prosthesis (Resnik et al., 2017). Items are rated on a 5-point scale based on the individual's capability of performing the activity, ranging from 1, very easy to perform the activity, to 5, cannot perform the activity, and the scores are summed (Resnik et al., 2017).

2.3.1.2 Performance Measures

Performance-based measures have advantages when assessing prosthesis user function when completing tasks resembling ADLs. They are a less biased way of quantifying upper body functionality compared to self-reported questionnaires. They also have the benefit of being reproducible (Wang et al., 2018), therefore are useful to compare across individuals or track progress over time. Most performance-based measures are scored based on speed or scored by an observer on a scale ranging from movement not being successful to movement being successful. Speed-based assessments, such as the Box and Block Test, Jebsen-Taylor Test of Hand Function, and Southampton Hand Assessment Procedure, rely on time to completion as their outcome measure (Wang et al., 2018). Improvements in time to completion do allow us to understand if an individual is improving their prosthesis use; however, they cannot capture any changes in movement patterns. Observer-based scales have been validated and may have the capacity to evaluate movement quality, as can the Activities Measure for Upper Limb Amputees (AM-ULA). However, they still rely on a subjective assessment of what successful movement entails (Wang et al., 2018). Several key performance-based assessments are discussed below in more detail.

Box and Block Test

The Box and Block test is a test of manual dexterity used to evaluate individuals with impairments in hand function (Mathiowetz et al., 1985). The test requires participants to move 2.5 cm cubes across a partition within a box. The dimensions of the box are 53.7 cm by 25.4 cm, and it is divided in the middle by a 15.2 cm high partition. Participants are given a 15 second practice trial followed by the actual testing trial, which lasts 60 seconds. Within that 60 seconds, participants are required to move as many cubes, from one side of the partition to the other, as they can (Mathiowetz et al., 1985). Benefits of the Box and Block Test are easy administration and normative population data available for comparison to impaired populations (Resnik et al., 2017).

Interrater reliability has been reported to be high for the Box and Block Test using the Pearson correlation coefficient, $r = 1.000$ and $r = .999$ for right and left hands, respectively (Mathiowetz et al., 1985). A strong correlation was also reported between the Box and Block Test and the AM-ULA ($r = .63$) (Resnik et al., 2013a). The Box and Block Test is a useful test to measure prosthesis user function considering it can distinguish between different levels of amputation (Resnik and Borgia, 2012). As expected, individuals with a transradial amputation displayed increased scores compared to individuals with more proximal amputations (Resnik et al., 2017). A modified Box and Block Test was also used to investigate performance differences when using different types of prostheses, namely a body-powered prosthesis followed by a myoelectric prosthesis after TMR surgery (Hebert and Lewicke, 2012).

Jebsen-Taylor Test of Hand Function (JTHF)

The JTHF uses time to completion for a variety of functional tasks as its measure of performance. It assesses dexterity, more specifically fine motor tasks, gross motor tasks, and carrying and handling objects, by administering seven subtests (Resnik et al., 2017). These subtests include writing a sentence, simulated page turning, simulated feeding, stacking checkers, picking up small objects and placing them in a container, and moving light and heavy cans (Jebsen et al., 1969). The JTHF has been used to assess function in upper limb prosthesis users (Resnik et al., 2014; Resnik and Borgia, 2012).

Both reliability and validity has been evaluated for the JTHF in prosthesis users. Test-retest reliability was excellent as measured by the ICC coefficient for four tests (Resnik et al., 2017). Correlations for the JTHF with both the AM-ULA and University of New Brunswick Test of Prosthetic Function (UNB) skill test ranged from r = .42 to r = .69 for tasks of the JTHF and the AM-ULA, and from r = .36 to .47 for the UNB subscales of prosthetic skill (Resnik et al., 2013a, 2013b).

Southampton Hand Assessment Procedure (SHAP)

The SHAP is a standardized test used by clinicians for non-disabled and impaired populations to assess hand function (Light et al., 2002). The SHAP contains 26 tasks, including abstract object tasks and ADLs (Burgerhof et al., 2017), with the goal of evaluating the effectiveness of a prosthesis user's terminal device and controller (Light et al., 2002). The abstract tasks contain two different types of objects, noncompliant dense materials and low-density materials. Each abstract task, based on object shape, elicits 1 to 2 of the following grasp patterns: spherical, tripod, tip, power, lateral, or extension grips. Both time to completion and each prehensile pattern contribute to the users' Index of Functionality (IOF) (Burgerhof et al., 2017). The ADLs selected for the SHAP also elicit the previously mentioned grasp patterns. Some of the ADLs include picking up a coin, undoing a button, simulated food cutting, simulated page turning, pouring water from a jug, and moving empty or full jars (Light et al., 2002). The SHAP has been shown to be reliable at both the interrater and intrarater levels. Moreover, the SHAP has the capacity to evaluate the functionality of passive, body-powered, and myoelectric prostheses (Light et al., 2002). Not only is the SHAP universal, but it is also quick to administer, taking only 20 minutes, and the test items can be easily transported. Therefore, it is applicable for use in a clinical environment (Burgerhof et al., 2017).

Activities Measure for Upper Limb Amputees (AM-ULA)

The AM-ULA is a performance-based measure that assesses individuals with an upper limb amputation on five categories, namely task completion, speed, movement quality, skillfulness of prosthesis use, and independence (Resnik et al., 2013a). The AM-ULA has the prosthesis user complete 18 self-care tasks, including some dressing tasks (put on t-shirt and button shirt, put on socks, tie shoes, and zip jacket), simulated eating tasks (use cup, use fork, use spoon, and pour soda), self-care tasks (brush hair, brush teeth), a reaching task (reach overhead), house-hold tasks (turn door knob, use phone, and fold towel), and table-top tasks (write word, use scissors, and hammer a nail) (Resnik et al., 2013a). Task scoring is based on speed of completion, movement quality, skillfulness, and independence. Speed of completion is the time it takes to complete the task and is compared to non-disabled speeds of completion. Movement quality is compared to natural-looking movement that would be performed by a non-disabled upper limb. Prosthesis user compensatory movements may be due to limitations from the prosthetic device, lack of planning or prepositioning, or compensatory movement strategies. These elements are considered by the rater when grading the prosthesis user. Skillfulness is assessed by the extent to which the prosthesis user uses his prosthetic device to complete the task and not simply as a passive stabilizer. Independence is assessed based on the prosthesis user requiring an assistive device to complete the task. When completing a given task, prosthesis users must accomplish all subparts of the task to receive a grade above 0. A grade of 0 signifies the prosthesis user was unable to complete the task (Resnik et al., 2013a).

Reliability, internal consistency, known group validity, and convergent validity were assessed when developing the AM-ULA. Reliability evaluated using the intra-class correlation (ICC) coefficient was .88 to .91 for test-retest reliability, and .84 to .85 for interrater reliability (Resnik et al., 2017). Known group validity was assessed by evaluating the scores of transradial prosthesis users and transhumeral prosthesis users. Scores decreased as the level of amputation increased (more distal to more proximal amputation). Convergent validity was assessed by investigating correlations between the AM-ULA and key dexterity measures from other upper limb assessments. Correlations ranged from .42 to .69, indicating a moderate correlation (Resnik et al., 2013a). Overall, the AM-ULA is a valid and reliable performance-based activity measure. A key benefit of this assessment is that it may be used with individuals using any type of prosthetic device, body-powered, myoelectric, or hybrid (Resnik et al., 2013a).

Assessment of Capacity for Myoelectric Control (ACMC)

The ACMC is a standardized clinical assessment designed to assess the functional capabilities and prosthetic control in myoelectric prothesis users only (Lindner et al., 2009). Advantages of the ACMC include the ability to administer the test in individuals with different levels of amputation and upper limb prosthesis users of all ages (Lindner et al., 2009), given the self-selected tasks that the participants may choose to complete. The ACMC requires that individuals complete 30 items, which can be grouped into four categories, gripping (12 items), holding (6 items), releasing (10 items), and coordinating between hands (2 items) (Resnik et al., 2017). The tasks are assessed by the therapist and are based on hand movement. Hand movement is rated on a 4-point scale, with 0 being not capable and 3 being spontaneously capable of performing the movement (Lindner et al., 2009).

2.3.2 Gained Insights

Having reliable and validated clinical assessments is key when working with individuals who have suffered upper limb loss and are using prosthetic devices. There needs to be a thorough way of measuring the efficacy of novel devices and therapeutic interventions and to track an individual's progress over time (Wang et al., 2018). Both self-report and performance-based clinical assessments may give useful information about the effectiveness of using a prosthetic device. If used in conjunction with each other, i.e., a self-report as well as a performance-based test, it may allow for even further specialized rehabilitation based on each individual's needs (Ostlie et al., 2011b). Self-report measures can give useful insights into the satisfaction of prosthesis users, which is valuable in future device development and therapy refinement (Heinemann et al., 2003). Observer-based performance measures may be advantageous to use over self-report measures when a therapist needs to rate the quality of motion of an individual and observe actual performance. Observer-based measures either compare quality of movement to non-disabled movement, evaluate how correct a movement is, or look at the independence of a user's actions (Wang et al., 2018). While observer-based measures rate the quality of movement, they do not quantify specific compensatory movements resulting from lost or compromised DoFs at the upper limb that are present in prosthesis users. Precisely quantifying compensatory movements is important given they may be a factor in the development of overuse injuries often seen in prosthesis users (Gambrell, 2008; Ostlie et al., 2011a) or discontinued use of a prosthesis altogether (Silcox et al., 1993).

One tool that allows identification and quantification of compensatory movements is the use of motion capture technology to analyze whole body kinematics; as kinematic assessment can quantify small changes in body movements. Such a tool may be greatly beneficial in evaluating novel prosthetic technologies that incorporate additional distal DoFs, which may in turn reduce compensatory movements. However, a kinematic assessment must still fulfill the criteria of being repeatable, reliable, and valid for application in the population of interest. The following section will introduce kinematic assessments and what has been previously reported in prosthesis user populations. It will also pinpoint the current gap in the field, justifying the work completed in this thesis on the development of a novel kinematic assessment for quantifying movement strategies in upper limb prosthesis users.

2.4 Kinematic Assessment

Kinematics is the study of motion of the limbs and joints of the body irrespective of forces (Hall, 2018). This type of analysis is ideal for evaluating movement in non-disabled populations as well as populations with impairments. There are some kinematic assessment protocols currently available that can quantify movement and compensations due to the use of various prosthetic devices. Kinematic assessments are typically used in a laboratory setting and are only available to clinicians through consultation to supplement results from clinical assessments, or used for research purposes. Kinematic assessment technologies may include simple goniometers, optical motion capture technology, markerless motion capture technology, or inertial measurement units. Currently, optical motion capture technology, also termed motion capture technology in subsequent chapters of this thesis, is most commonly used in research environments, but novel technologies such as markerless motion capture technology and inertial measurement units are becoming more readily available with increased information on validity and reliability (Tanaka et al., 2018). Key features of these novel motion capture technologies include light weight sensors attached to the human body and systems that do not obstruct movements or tasks analyzed (Kramer et al., 2006).

2.4.1 Goniometry

A simple, inexpensive, and easy to use tool to measure joint angles is a goniometer. There are various types of goniometers, including universal, fluid, and electrogoniometers. Universal goniometers are easy to use, but are restricted to simple joint movements or static joint positions, and at only one joint at a time (Yoshida et al., 2012). These are useful for measuring passive RoM at specific joints. While these goniometers are simple to use, their utility is limited when the goal is to quantify functional RoM. Moreover, a good understanding of joint anatomy is needed to locate the center of rotation and longitudinal axes of limb segments for accurate readings (Hall, 2018). Fluid goniometers are made of a circular clear tube filled with liquid. As the device is rotated, the fluid moves relative to the graduated disk and makes an angle equal to the angular displacement of the base. This type of goniometer works independently of the center of rotation. It has been reliably used for measurements at the knee and elbow (Rome and Cowieson, 1996). Electrogoniometers contain a strain gauge steel strip placed between two plastic sections; when deformed based on the angular displacement of the joint, they display the reading digitally on the display unit. The beginning of the movement is set to zero and the end of the motion will be displayed as the angular displacement of the movement (Goodwin et al., 1992). This type of goniometer allows for quantification of functional RoM at individual joints and is easy to use; therefore, this tool is clinically accessible. Goniometers, however, are limited in their accuracy and utility when the goal is to assess multiple DoFs at the upper limb, given that errors reported at the hand are up to 12% of RoM (Jonsson et al., 2007).

2.4.2 Optical Motion Capture Technology

Optical motion capture technology has been used for kinematic assessments for several decades. This system uses two or more cameras placed in specific locations surrounding a well-defined capture volume. The entire task must be contained within the specific capture volume for proper tracking of body segments. This can lead to potential complications when attempting to track body segments during tasks that require large RoM, potentially exceeding the capture volume (Kramer et al., 2006). Two types of markers are available, passive markers and active markers (Kramer et al., 2006). Passive markers are covered with reflective material and affixed to study participants or patients on strategic locations on the body, either on bony landmarks or segments. Each marker has to be captured by at least two cameras in order for its three-dimensional location to be identified by the system (Leardini et al., 1999). Newer cameras contain LED rings around the camera lens. The LEDs act like a strobe light and reflect off the markers. Active markers are small LED markers that are placed on the participant's limbs. They emit light at specific frequencies, which is captured by the cameras (Kramer et al., 2006). Both systems have their advantages and disadvantages. An advantage for passive markers is how simple they are to attach to the body using double-sided tape. They are typically light weight and not intrusive to movement. The disadvantage lies in the post-processing phase, which is labour intensive if there is significant marker occlusion or if automatic labelling is difficult, as may occur with certain movements. The post-processing requirements increase for marker sets that require numerous markers or where the markers are close together. One of the main disadvantages of active markers is the system of cables required to power the markers. These cables can be intrusive for certain movements and tasks.

Extensive post-processing is often required when using optical motion capture technology with reflective markers. The 3D coordinates of the markers in the global reference frame are the output of the data acquisition using this motion capture technology. Each body segment requires a minimum of three markers or reference points in order for a body-fixed coordinate system to be created, and to allow for determination of 3 rotational DoF motion, more specifically, flexion/extension, lateral bending or abduction/adduction, and axial rotation, of that body segment (Boser et al., 2018). Optical motion capture technology typically cannot provide real-time data for feedback to the investigator, clinician, or patient, which is another disadvantage of this type of system (Kramer et al., 2006).

One of the key differences between using motion capture technology to asses upper limb movement versus clinical performance-based measures as described in the above section is the selection of tasks. When developing a clinical performance-based measure, any functional task or ADL may be chosen, given that the analysis will be observer-based. This unfortunately is not the case for optical motion capture technology. Tasks must be carefully selected to be amenable to motion capture. In other words, tasks must have distinct movement sequences that are clearly defined such that data can be averaged across trials and participants, if reproducibility is desired. Tasks must also consider the position of the cameras and markers on the body and ensure that minimal marker occlusion occurs. Therefore, practical, goal-oriented, and 'real world' tasks such as folding a towel, which are common in clinical assessments, would be difficult to properly capture using motion capture technology, given that the risk of marker occlusion would be high. Individual towel folding techniques, or a lack of task standardization would also introduce high variability in the kinematic data.

2.5 Upper Body Kinematics in Prosthesis Users

Kinematic assessments of prosthesis users are becoming more common in clinical and research domains (Hebert and Lewicke, 2012; Hussaini et al., 2017; Major et al., 2014). Clinical assessments are useful for assessing overall functional ability of a prosthesis user; however, they typically do not have the capacity to clearly identify movement strategies or compensatory movements present at the upper body. Measuring kinematics in prosthesis users is important since even a slight change in the prosthetic device can lead to movement changes elsewhere in the body (Bertels et al., 2009). In the case where the movement changes are adaptive, they could reduce the rate of use of the intact body segments, therefore reducing overuse injuries (Bertels et al., 2009). To date, roughly a dozen studies have been reported in the literature with upper limb prosthesis users, evaluating their kinematic movement strategies while performing tasks mimicking ADLs. Unfortunately, minimal consistency is present across studies based on sample size, joints and DoFs selected, tasks selected, and results reported. This makes comparison across studies difficult. However, being familiar with the current literature can guide future research to fill missing gaps and provide more data to compare with previous research.

2.5.1 Study Sample Size and Participant Characteristics

Prosthesis user kinematic studies thus far have been limited to small sample sizes ranging from one participant (Abd Razak et al., 2013; Carey et al., 2009; Hebert and Lewicke, 2012) to up to ten participants (Badin et al., 2017; Hebert et al., 2019; Metzger et al., 2012). These small sample sizes, especially when prosthetic technologies studied combine both body-powered and myoelectric prostheses as in Metzger et al. (Metzger et al., 2012), make it difficult to generalize trends to a wider population of individuals who use prosthetic devices. The small sample sizes are likely due to the difficulty of recruiting participants, but also the nature of kinematic assessments. Motion capture technology is currently expensive and requires a significant amount of post-processing, often making this technology difficult to access in a clinical environment and time intensive in a research environment.

Upper limb prosthesis user studies may involve individuals with either transradial or transhumeral limb loss, although most studies have focused on individuals with a transradial amputation (Abd Razak et al., 2013; Bertels et al., 2009; Bouwsema et al., 2012, 2010; Carey et al., 2009, 2008; Cowley et al., 2016; Hussaini et al., 2017; Major et al., 2014). Although compensatory mechanisms might be expected to be vastly different between individuals using a prosthetic elbow, which might be locked, and individuals with a natural elbow as those with a transradial amputation, recent studies indicate compensations may in fact be quite similar (Hebert et al., 2019), highlighting the need to continue studying this area. Pertaining to prosthetic technology, most studies currently evaluate myoelectric users (Bertels et al., 2009; Bouwsema et al., 2012, 2010; Carey et al., 2008), with only a few studies investigating body-powered prosthesis users (Carey et al., 2009; Hebert and Lewicke, 2012). Clearly defining other participant characteristics such as age and time since amputation, in addition to level of amputation and prosthetic components, is crucial given these may impact movement strategies as well (Bennett et al., 2012; Huinink et al., 2016a).

2.5.2 Measures and Degree of Freedom Selection

Most prosthesis user kinematic studies selected similar measures to quantify movement at specific DoFs. The most common kinematic measure was RoM (Bertels et al., 2009; Carey et al., 2009, 2008; Hebert and Lewicke, 2012; Major et al., 2014; Metzger et al., 2012). Some studies also reported on peak angles for specific tasks (Abd Razak et al., 2013; Badin et al., 2017; Carey et al., 2008; Hebert and Lewicke, 2012; Hussaini et al., 2017). Trunk DoFs are often included in an analysis of upper body movement since the trunk is a major area of compensation in prosthesis users. Trunk flexion/extension and lateral bending were reported in most studies (Bouwsema et al., 2012; Carey et al., 2008; Hebert and Lewicke, 2012; Hussaini et al., 2017; Major et al., 2014; Metzger et al., 2012), and only three studies included trunk axial rotation (Bouwsema et al., 2012; Hussaini et al., 2017; Major et al., 2014). These studies reported consistent findings, showing a statistically significant increase in trunk movement, for all three DoFs, compared to non-disabled populations (Carey et al., 2008; Major et al., 2014; Metzger et al., 2012). Hebert and Lewicke, in addition to Hussaini et al., reported similar trends; however, they did not comment on the statistical significance of their results (Hebert and Lewicke, 2012; Hussaini et al., 2017).

Shoulder movement in prosthesis user studies was not reported to the same extent as trunk movement. However, similar to the trunk, shoulder flexion/extension and shoulder abduction/adduction (Bertels et al., 2009; Bouwsema et al., 2012; Carey et al., 2009, 2008; Major et al., 2014) were more frequently reported than shoulder internal external rotation (Bertels et al., 2009; Bouwsema et al., 2012). Carey et al. found that their participants used a significantly smaller amount of shoulder flexion (Carey et al., 2008). Major et al. reported their participants using more shoulder abduction (Major et al., 2014), which was similar to Metzger et al., who reported increased shoulder path movement (Metzger et al., 2012). It should be noted that results pertaining to the differences in shoulder movement could be task dependent, given that there was a wide range of tasks observed among studies. In fact, task dependence and the effect on kinematic strategies was confirmed by the report of Hebert et al. (Hebert et al., 2019).

Elbow flexion/extension was reported in six studies, of which five had transradial prosthesis users as their participants (Badin et al., 2017; Bertels et al., 2009; Bouwsema et al., 2012; Carey et al., 2008; Major et al., 2014). Hebert and Lewicke reported on elbow movement for a transhumeral prosthesis user using both a body-powered and myoelectric device (Hebert and Lewicke, 2012). The myoelectric device used in the study allowed for four-site muscle control of elbow flexion, elbow extension, hand open, and hand close, and displayed changes in elbow movement throughout the task (Hebert and Lewicke, 2012).

There is minimal reporting in the literature on wrist movement in the context of upper body movement. Only a study by Abd Razak et al. reported on wrist flexion/extension since their participant had a biomechatronic prosthetic device with wrist movement (Abd Razak et al., 2013).

Otherwise, most current prosthetic devices used by individuals with an amputation do not incorporate wrist movement; therefore, it is not usually reported in prosthesis user studies.

2.5.3 Task Selection

A key aspect that makes comparison across prosthesis user kinematic studies currently difficult is the lack of consistency in task selection. Up to thirty-four different tasks have been reported in the prosthesis user kinematic literature (Table A.1 in Appendix A). The reported tasks can be divided into categories of similar tasks including RoM tasks, tasks mimicking ADLs, simple grasping tasks, and ADLs such as activities related to feeding, self-care activities, and house-hold activities. RoM tasks include an elbow flexion task (Carey et al., 2009) and wrist movement tasks (Abd Razak et al., 2013). Examples of tasks that mimic ADLs are moving the hand to different parts of the body such as the anterior superior iliac spines, to the mouth, sternum, face, and ipsilateral hip pocket (Bertels et al., 2009). Tasks related to feeding include drinking from a cup (Carey et al., 2009, 2008), cutting, slicing, stirring, and eating (Hussaini et al., 2017). Self-care activities include applying deodorant and perineal care (Cowley et al., 2016) as well as dressing tasks (Cowley et al., 2016; Metzger et al., 2012). House-hold activity tasks range from opening a door (Carey et al., 2009, 2008) to page turning (Major et al., 2014), and lifting and transferring a weighted object (Major et al., 2014). Few tasks were observed across more than one group of authors, but those that were included a direct grasping task (Badin et al., 2017; Bouwsema et al., 2012, 2010) and a cutting task (Hussaini et al., 2017; Major et al., 2014). The wide range of tasks reported can be justified given the wide range of tasks the upper limbs are capable of. Understanding how prosthesis users compensate for missing DoFs for many different activities they would encounter in their everyday life enhances the literature; however, it does make it difficult for comparison and generalization purposes given the small sample sizes currently available that are being reported on each task.

2.6 Conclusion

With the continued advancement of prosthetic devices, it is essential to have standardized assessment tools. A wide range of clinical assessment tools have been established and validated, both self-report- and performance-based. Using these tools does allow a general understanding of prosthesis user function. Moreover, these assessments are easily accessible to clinicians, quick to administer, and inexpensive. A disadvantage of clinical assessment tools is their inability to quantify specific compensatory movements of interest to researchers or clinicians. Currently, clinical assessment tools are a subjective method of assessing movement via a trained observer, which may not be as sensitive as a precise quantitative analysis that is facilitated through a kinematic assessment. The latest advancements in prosthetic technology development include additional DoFs in the hand and wrist via the use of more actuators (Semasinghe et al., 2016) and improved control strategies (Xu et al., 2018). Such improvements are geared towards allowing more natural movement at the prosthetic hand, which could in turn reduce some of the compensations observed in prosthesis users. Kinematic assessments using motion capture technology allows for the precise quantification of joint movement for all DoFs at the upper body. In light of the topics discussed in this chapter pertaining to prosthetic technology improvements, clinical assessments in prosthesis users, and the lack of standardization present in kinematic assessments, there is a need for the development of a novel kinematic assessment that focuses on using complex tasks that are representative of ‘real-world’ activities to quantify changes in upper body kinematics at all DoFs. Therefore, the following chapters of this thesis focus on a literature review of kinematic assessments in a non-disabled population, the fundamental development and validation of the novel kinematic assessment in a non-disabled population, and an illustration of the use of this kinematic assessment in a sample population of prosthesis users.

As part of the development effort, an initial emphasis will be placed on task selection, where tasks should be functional in nature (Taylor et al., 2018) and challenge prosthesis user capabilities. Following task development, a comprehensive analysis of hand function and angular kinematics in non-disabled individuals will be presented given that, prior to applying new tasks to prosthesis users, a clear understanding of natural non-disabled movement is imperative (Wang et al., 2018). Therefore, the next three chapters of this thesis will cover non-disabled movement characteristics for functional tasks. Chapter 3 will provide a review of the literature pertaining to kinematic models used with motion capture technology to assess upper body movement in non-disabled individuals. Chapters 4 and 5 will validate the development of our novel kinematic assessment with two standardized functional tasks in a non-disabled population and present results on hand function and angular joint kinematics. Chapter 6 will focus on applying the developed and validated kinematic assessment to a body-powered prosthesis user population, illustrating its application in prosthesis users and ability to quantify compensatory movement strategies.

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Chapter 3. Review of Upper Body Kinematic Protocols for Non-Disabled Populations Using Optical Motion Capture Technology

The material presented in this chapter has been published in the article:

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The content of this chapter is identical to the material presented in the publication, except for the text formatting which was done according to University of Alberta requirements.

3.1 Abstract

Quantifying 3D upper body kinematics can be a valuable method of assessing upper limb function. Considering that kinematic model characteristics, performed tasks, and reported outcomes are not consistently standardized and exhibit significant variability across studies, the purpose of this review was to evaluate the literature focused on upper body kinematics in non-disabled individuals via optical motion capture. Specific objectives were to report on the kinematic model characteristics, performed functional tasks, and kinematic outcomes, and to assess whether kinematic protocols were assessed for validity and reliability. Five databases were searched. Studies applying anatomical and/or cluster marker sets, along with optical motion capture, and presenting normative data on upper body kinematics were eligible for review. Information extracted included model characteristics, performed functional tasks, kinematic outcomes, and validity or reliability testing. 804 publication records were screened and 20 reviewed based on the selection criteria. Thirteen studies described their kinematic protocols adequately for reproducibility, and 8 studies followed International Society of Biomechanics standards for quantifying upper body kinematics. Six studies assessed their protocols for validity or reliability. While a substantial number of studies have adequately reported their protocols, more systematic work is needed to evaluate the validity and reliability of existing protocols.

3.2 Introduction

Upper limb function can be impaired by a variety of injuries to the neuromuscular or musculoskeletal systems, including spinal cord injury, stroke, or cerebral palsy (Klingels et al., 2012; Ross et al., 2016; Velstra et al., 2014). Such impairments can greatly affect one's ability to perform ADLs. Objectively quantifying the kinematics of the upper body during functional tasks could provide an important step towards understanding movement disorders of the upper limbs and evaluating the effect of rehabilitation interventions (Yang et al., 2002). While methods such as inertial measurement units and magnetic tracking systems show promise for quantifying upper limb motion particularly in ambulatory situations, the use of optical motion capture systems using body markers is currently widely used in clinical and research applications (van Andel et al., 2008; Williams et al., 2006). This technology, which uses two or more cameras to triangulate the 3D position of markers in a capture volume, tracks one of two types of markers: (1) passive markers, which are beads covered in reflective material; or (2) active infrared light-emitting diodes, which are paired with a control unit that pulses light from the infrared light-emitting diodes to identify their locations over time (Robertson, 2014). Irrespective of the marker type used, optical motion capture can provide kinematic information on upper body function in an objective fashion, thereby complementing clinical assessment techniques.

Upper body motion is highly variable and complex, often challenging all DoFs in the kinematic chain during functional tasks. Such variability and complexity makes movement standardization for the purpose of kinematic assessment difficult (Rau et al., 2000; Yang et al., 2002). In response to this intrinsic variability and complexity, unique experimental protocols are often developed to assess upper body kinematics. Different marker configurations, both in terms of types and locations, have been used to track body segments (Anglin and Wyss, 2000), and various mathematical conventions are used for calculating joint angles. There is also substantial variability in the functional tasks used and the kinematic outcomes reported, which inhibits the ability to compare data sets within normative and across impaired populations (Anglin and Wyss, 2000). These factors emphasize the importance of a given protocol to have documented validity and reliability to ensure its repeatability and clinical applicability.

Given these challenges, we focused our review on the following methodological factors: (1) the characteristics of the marker set used – including the type of marker set, the calibration method, the DoFs, and the type of local coordinate system (LCS) definition used (overall referred to as *kinematic model*); (2) the types and characteristics of the tasks performed; (3) the kinematic outcomes obtained; and (4) the validity and reliability of the kinematic protocols reported.

3.2.1 Types of Upper Body Marker Sets

Two types of body-attached marker sets are commonly used in kinematic studies; an anatomical or cluster marker set. Both types are independent of the investigated DoFs and rely on bony anatomical landmarks; however, the cluster marker set typically tracks only the clusters during functional tasks (Williams et al., 2006). The *anatomical marker set* uses bony anatomical landmarks as the attachment site of single markers (Alt Murphy et al., 2006; Cimolin et al., 2012; Gates et al., 2016; Hebert et al., 2014; Lobo-Prat et al., 2012; Murgia et al., 2010; Pereira et al., 2012; Petuskey et al., 2007; Rab et al., 2002; Reid et al., 2010; Ricci et al., 2015; Schmidt et al., 1999; Yang et al., 2002). Anatomical landmarks are characterized by a layer of soft tissue covering a bony prominence, and require marker placement via clearly established and well-practiced palpation procedures to avoid errors, especially across administrators (Della Croce et al., 2005). Although common palpation errors of up to a few millimeters have been shown to result in angular errors of only a few degrees, significant inter-participant differences can pose a threat to validity and reliability due to large variability (de Groot, 1997). The aim of an anatomical marker set is to reliably estimate the instantaneous orientation of each segment's LCS relative to a baseline that is anatomically meaningful (e.g., 0 degrees in an anatomical position). Each LCS is obtained by using at least three anatomical landmarks on a segment to construct an anatomical reference frame that is affixed to that segment (Cappozzo et al., 2005). The reliability of LCS definition increases as more anatomical landmarks are tracked, and when this redundancy of information is used with more advanced least-squares minimization techniques (Chiari et al., 2005). However, using additional markers results in an increased administrative burden which is a consideration in clinical applications.

The *cluster marker set* uses clusters of markers that are geometrically arranged and mounted on an elastic band or a rigid or semi-rigid plate (Dennerlein et al., 2007; Gates et al., 2016; Jaspers et al., 2011b; Lobo-Prat et al., 2012; Qin et al., 2014, 2011; Reid et al., 2010; Schmidt et al., 1999; Thrasher et al., 2010; van Andel et al., 2008; Vanezis et al., 2015; Williams et al., 2006). For some lower limb segments, this technique has been shown to reduce soft tissue artifacts related to soft tissue movement over bone, as only the markers on the plates are tracked during functional tasks (Manal et al., 2000). However, there is limited evidence on the use of marker clusters to reduce the incidence of soft tissue artifacts in the upper limbs. Guidelines for creating cluster marker sets have been established in an attempt to reduce the propagation of error to the estimation of the LCS (Cappozzo et al., 1997), including: (1) at least four markers per cluster should be used; (2) the size index, which is the root mean square distance of the markers from their mean position, should be as high as possible (but limited by body segment size); (3) clusters should be positioned at locations that will minimize overall skin movement artifacts; and (4) effects of muscular contraction patterns should be considered as they can cause deformations and/or displacements of clusters. Guidelines (3) and (4) in particular may reduce, although not eliminate, the potential effect of soft tissue artifacts (Cappozzo et al., 1997). In addition to cluster placement, some form of cluster calibration that captures a cluster's orientation relative to the location of relevant anatomical landmarks is still required (Gates et al., 2016). This calibration approach typically relies on anatomical landmark identification, associated with the previously described limitations.

3.2.2 Degrees of Freedom and Conventions for Calculating Joint Angles

Upper body segments that are generally included in kinematic analyses are the head, trunk, pelvis, upper arms, forearms, and hands (Slavens and Harris, 2008). The most difficult joint motions to report relate to the shoulder complex, consisting of glenohumeral, acromioclavicular, sternoclavicular, and scapulothoracic articulations. Since motions of the scapula and clavicle are difficult to track using skin-mounted markers, they are often omitted in upper body kinematic analyses (Anglin and Wyss, 2000). Instead, typically three-DoF movements of the humerus relative to the thorax are focused on (flexion/extension, abduction/adduction or horizontal abduction/adduction, and internal/external rotation) (Anglin and Wyss, 2000; Cirstea and Levin, 2000). Movements of the elbow and forearm are reported as elbow flexion/extension and forearm pronation/supination (Jazrawi et al., 2012). The wrist, a two-DoF joint, allows flexion/extension and radial/ulnar deviation (Barr and Bear-Lehman, 2012). The neck and trunk are represented with three DoFs each, allowing flexion/extension, lateral bending, and axial rotation (Vette et al., 2012).

Once the DoFs of interest have been identified, different mathematical conventions can be used to define LCS and calculate the angular joint kinematics. *Helical Angles* describe a segment's movement in terms of a translation along and a rotation about a single axis (Robertson, 2014), which is generally difficult to interpret clinically. *Cardan-Euler Angles* is a method that obtains angular kinematics from right-hand orthogonal LCS, requiring the selection of a specific rotation sequence. *Joint Coordinate System*, a method presented by Grood & Suntay, creates LCS with two body-fixed axes and a third floating axis whose rotations give rise to specific joint angles. Key features of this method are that the obtained LCS is non-orthogonal and that the rotation sequence does not need to be specified (Grood and Suntay, 1983). It has, however, been shown that the *Joint Coordinate System* is mathematically equivalent to the specific Cardan sequence that yields joint flexion/extension, abduction/adduction, and internal/external rotation (MacWilliams and Davis, 2013). Due to these characteristics, it is not surprising that *Cardan-Euler* A*ngles* are currently the most commonly used method for calculating joint kinematics. Different *Cardan-Euler* rotation sequences may be selected depending on the task or joint being evaluated. This option is specifically important for motion of the humerus relative to the thorax as several rotation sequences may result in Gimbal lock depending on the performed task (Bonnefoy-Mazure et al., 2010).

The shoulder complex is the most challenging articular structure to represent when attempting to calculate 3D angular motion. Two methods have been commonly used to describe motion of the humerus relative to the thorax: the Cardan-Euler rotation sequence to capture shoulder flexion/extension, abduction/adduction, and internal rotation (Phadke et al., 2011), or the globe system. The globe system, as defined by Pearl et al. (Pearl et al., 1992), describes the position of the humerus relative to the thorax by using latitudes and longitudes along a globe. This system provides the angle of the plane of elevation, the angle of elevation, and the angle of rotation. The angle of the plane of elevation is defined by longitudes, for which the humerus moves from a non-elevated position to an elevated position, with the coronal plane corresponding to 0 degrees. The angle of elevation is defined by latitudes and indicates how the humerus deviates from the neutral anatomical position. Finally, the angle of rotation is defined as the angle of the forearm with respect to the horizontal plane. Note that this angle might be difficult to obtain in cases where the forearm is nearly straight or has minimal elbow flexion as the elbow should be in a 90° of flexion position (Doorenbosch et al., 2003; Pearl et al., 1992).

The International Society of Biomechanics (ISB) has published recommendations on LCS definitions to promote the standardization of protocols for upper limb motion analysis (Wu et al., 2005), which attempts to address the lack of consistency across studies in terms of defining LCS and the utilized Cardan-Euler rotation sequence. Nonetheless, there are currently dichotomous views on how LCS should be defined: some researchers have criticized the ISB recommendations on the basis of them not being practical for clinical use (Rab et al., 2002), whereas others are highly in favor of them as they facilitate consistency across studies, resulting in more robust and valuable findings (Kontaxis et al., 2009).

3.2.3 Functional Upper Limb Tasks

A wide variety of functional tasks have been used for kinematic assessment of the upper limbs. Some researchers have analyzed directed movements (such as reaching movements with a defined start and end location; path drawing that follows a desired path with the same start and end point; or specific RoM movements), while others use tasks that mimic ADLs (De Los Reyes-Guzmán et al., 2014; Tuijl et al., 2002). Both approaches involve functional movements, but with different levels of constraint and complexity. Researchers have advocated that the chosen upper limb tasks be goal-oriented and of a standardized nature to attain consistent performance (Hebert et al., 2014). The use of standardized upper limb tasks is especially important when considering that different individuals or populations may use different strategies to complete a given task, therefore making comparisons across tasks even more difficult (Kim et al., 2014).

3.2.4 Kinematic Outcomes

Various aspects of movement can be analyzed with kinematic outcomes, including active or passive RoM, movement velocity, and hand trajectory (De Los Reyes-Guzmán et al., 2014). Velocity profiles have the potential to provide useful insights into movement smoothness by examining peak velocities and the number of movement units. From the acceleration profile, the number of zero-crossings and jerk attributes have been used to characterize movement smoothness (Alt Murphy and Häger, 2015). Furthermore, inter-joint movement coordination and joint synchronization can be characterized by cross-correlating angular kinematics of different joints (Alt Murphy and Häger, 2015). Interpreting these types of outcomes from upper body kinematics of non-disabled movement can enhance our mechanistic knowledge on how functional tasks are being completed, and can serve as a benchmark for investigating impaired populations.

3.2.5 Validity and Reliability of Kinematic Protocols

When using a kinematic model and functional task, it is important to assess the validity and reliability of the kinematic outcomes. While several types of validity exist (i.e., face and content validity, criterion validity, and construct validity), the term generally refers to the extent that the outcomes of a given test are a good representation of true human behavior (Portney and Watkins, 2009), or the extent that the test is measuring what it is presumed to be measuring (Jerosch-Herold, 2005). To fulfill criterion validity, kinematic outcomes should be correlated with clinical scales (De Los Reyes-Guzmán et al., 2014), or a gold standard for measuring upper body kinematics (Jerosch-Herold, 2005). Reproducibility and meaningful data interpretation also requires reliability, or consistency in the reported outcomes, which should be reported in terms of both intra- and inter-tester reliability (Jerosch-Herold, 2005).

3.2.6 Review Objectives

The study of upper body kinematics can give accurate and objective information about motor strategies, compensatory movements, and joint coordination strategies, and is therefore a powerful tool for both clinical and research domains (De Los Reyes-Guzmán et al., 2014). Kinematic analyses can be especially beneficial for assessing movement disorders and for evaluating rehabilitation strategies in comparison to non-disabled performance (Yang et al., 2002). This review will discuss the methodologies and results of published studies that used optical motion capture of the upper body to define normative kinematics for a variety of upper limb tasks, understanding that normative results can be used as a benchmark for comparisons against impaired populations. The objectives of this review are to: (1) characterize the kinematic models used in non-disabled populations, with a specific focus on type of marker set, selected DoFs, and LCS definition; (2) describe the utilized functional tasks and reported kinematic outcomes; and (3) examine whether the kinematic protocols were assessed for validity and reliability. Using conclusions from the review of the current literature, recommendations for future research studies and for clinical use will be made.

3.3 Methods

3.3.1 Search Strategy

An electronic search of the following databases since their inception to December 2016 was performed: EMBASE (1974), MEDLINE (1946), Web of Science (1864), Cochrane Library (1993), and Scopus (1960). Medical subject headings (MeSH) were matched to key search terms. Most search terms were truncated to cover as many variations of a given term as possible. Keywords searched with specific truncations are presented in Table 3-1. A manual search was conducted to check if any relevant papers had been missed in the database search. The complete search strategy for EMBASE is presented in Table 3-2.

Table 3-1 Terms used in database search with truncations identified with an asterisk (*).

Search Terms
arm*
upper body
upper extremit*
motion analys*
motion captur*
3D kinematic*
three dimensional kinematic*
kinematic*

Table 3-2 EMBASE search strategy.

#	Searches
1	(arm* or upper body or upper extremit*)
2	(motion analys* or motion captur* or (kinematic adj2 analys*) or 3D kinematic* or three dimensional kinematic*)
3	Kinematic*
4	Robot*
5	(1 and 2 and 3) not 4

3.3.2 Inclusion and Exclusion Criteria

Inclusion criteria for the review were: (1) non-disabled participants; (2) at least two joints from the upper extremity kinematic chain studied (shoulder, elbow, wrist, and/or trunk); (3) functional tasks performed with at least one upper extremity; (4) 3D kinematic data collected via an optical motion capture system; (5) use of anatomical or cluster sets of body-attached markers; and (6) reporting of joint angle trajectories and/or associated kinematic measures. Articles were excluded if they met one or more of the following: (1) studied only an impaired population; (2) studied only one joint or segment of the upper extremity kinematic chain; or (3) presented upper limb kinematics for sport-related activities (e.g., golf). Articles reporting only on an impaired population were excluded as the goal of this review was to characterize studies attempting to create a normative data set for functional upper limb tasks. While full scientific articles with abstracts were included, conference proceedings or manuscripts in a language other than English were not.

3.3.3 Data Extraction and Quality Assessment

The main categories for data extraction were: type of markers, number of markers, marker placement location, calibration method, body segments, DoFs studied, method of joint angle calculation, following of ISB guidelines, functional tasks used, reported kinematic outcomes, and information on protocol validity and reliability. Information extracted from the articles was summarized in tables. The quality of the selected studies, in terms of their validity and reliability, was assessed using a framework developed by Jerosch-Herold (Jerosch-Herold, 2005). Responsiveness was not included as the studies were focused on non-disabled populations and did not intend to capture change over time. Since errors could be introduced into the kinematic protocol in several ways, criterion validity was assessed by determining whether a study's protocol was compared to a gold standard or by cross-validation against another measure. Measures of reliability were extracted for both intra- and inter-tester reliability.

3.4 Results

3.4.1 Study Selection and Characteristics

A total of 1554 articles were obtained by means of the database search. From the identified articles, 750 duplicates were removed. The titles and abstracts of the remaining 804 articles were screened for inclusion by two independent assessors (AV & PJ). Following title and abstract screening, 721 papers were discarded, resulting in 83 articles that were identified for full text review. From those 83 articles and 10 articles found through a manual search, 20 met the criteria for inclusion. A flow diagram of the study selection process is shown in Figure 3-1.

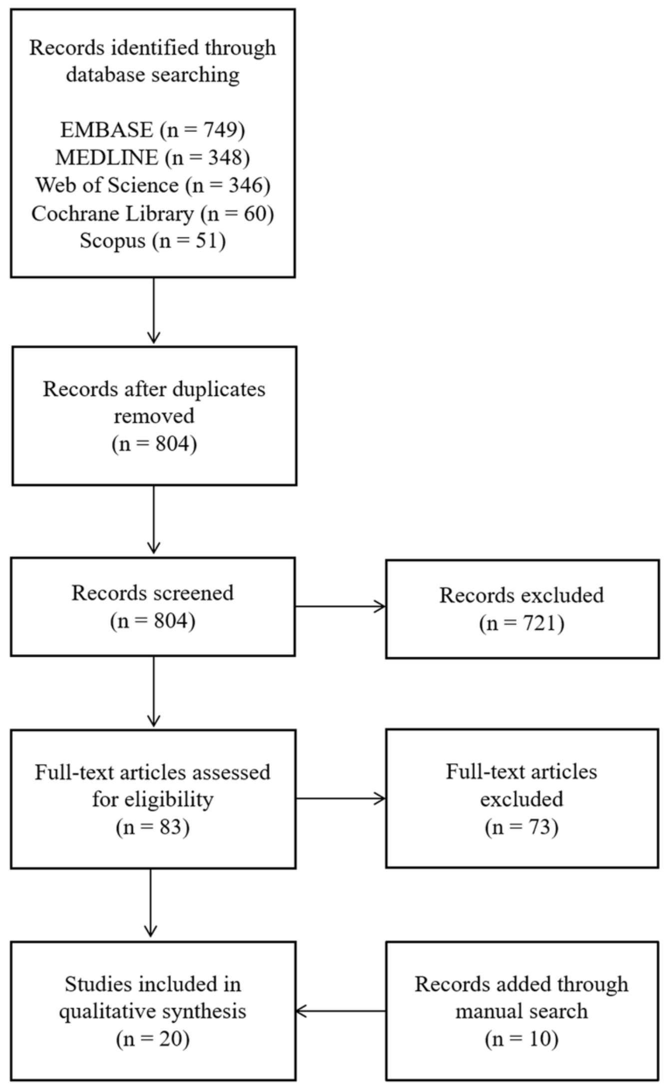

Figure 3-1 Study selection flow diagram for the searched databases.

Study characteristics are presented in Tables 3-3 and 3-4. For each article, Table 3-3 summarizes the kinematic model characteristics, including the type of marker set, number and location of markers, calibration method, upper body segments and DoFs studied, method for joint angle calculation, and whether the study followed ISB guidelines. Table 3-4 presents the functional task(s) studied, the reported kinematic outcomes, and the motion capture system used. Available data were extracted and unavailable information was identified as NR (not reported).

Table 3-3 Description of kinematic model characteristics used by selected studies. Categories include type of marker set, number and location of markers, calibration method, segments and DoFs studied, method for defining local coordinate systems (LCS), and whether a study followed ISB guidelines

Authors	Type of Marker Set	Number of Markers	Location of Markers	Calibration Method	Segments	DoFs	LCS Definition / Rotation Sequence	ISB
Alt Murphy et al. (2006)	Anatomical	9	Left cheek Sternum Acromion Lateral epicondyle Ulnar styloid 3rd MCP 2nd DIP	NR	Trunk Upper arm Forearm	Shoulder flexion/extension Shoulder abduction/adduction Elbow flexion/extension	NR	NR
Cimolin et al. (2012)	Anatomical	12	C7 Sternum Acromion Lateral epicondyle Radial styloid Ulnar styloid ASIS	NR	Trunk Upper arm Forearm	Shoulder flexion/extension Shoulder abduction/adduction Shoulder internal/external rotation Elbow flexion/extension	Cardan-Euler / X-Y-Z	No
Dennerlein et al. (2007)	Cluster	13	*3-marker cluster:* Hand Forearm Upper arm Thorax *Anatomical:* Finger	NR	Trunk Upper arm Forearm Hand Finger	Shoulder flexion/extension Elbow flexion/extension Wrist flexion/extension MCP flexion/extension	NR	NR

Authors	Type of Marker Set	Number of Markers	Location of Markers	Calibration Method	Segments	DoFs	LCS Definition / Rotation Sequence	ISB
Gates et al. (2016)	Cluster Anatomical	37	*4-marker cluster:* Upper arm Forearm *Anatomical:* Xiphoid process Sternal notch C7 T8 Acromion Medial epicondyle Lateral epicondyle Radial styloid Ulnar styloid 3rd MCP 5th MCP ASIS PSIS Iliac crest	Static	Pelvis Trunk Upper arm Forearm	Pelvic axial rotation Pelvic obliquity Pelvic tilt Trunk flexion/extension Trunk lateral flexion Trunk axial rotation Shoulder plane of elevation Shoulder elevation Shoulder internal/external rotation Elbow flexion/extension Elbow pronation/supination Wrist flexion/extension Wrist ulnar/radial deviation	Cardan-Euler / Y-X-Y Z-X-Y	Yes
Hebert et al. (2014)	Anatomical	15	C7 T8 Acromion Lateral epicondyle Medial epicondyle Ulnar styloid Radial styloid Head of 3rd MCP	Static	Trunk Upper arm Forearm Hand	Trunk flexion/extension Trunk lateral flexion Trunk axial rotation Shoulder flexion/extension Shoulder abduction/adduction Shoulder axial rotation Elbow flexion/extension Wrist flexion/extension	Cardan-Euler	No

Authors	Type of Marker Set	Number of Markers	Location of Markers	Calibration Method	Segments	DoFs	LCS Definition / Rotation Sequence	ISB
Jaspers et al. (2011)	Cluster	17	*3-marker cluster:* Thorax Acromion Hand *4-marker cuff:* Later upper arm Forearm	Digitization	Trunk Scapula Upper arm Forearm Hand	Trunk flexion/extension Trunk lateral flexion Trunk axial rotation Scapula protraction/retraction Scapula medial/lateral rotation Scapula tilting Shoulder plane of elevation Shoulder elevation Shoulder internal/external rotation Elbow flexion/extension Elbow pronation/supination Wrist flexion/extension Wrist ulnar/radial deviation	Cardan-Euler	Yes
Lobo-Prat et al. (2012)	Cluster Anatomical	26	*3-marker cluster:* Upper arm *Anatomical:* Glabella Cheekbone Xiphoid process Sternal notch C7 Anterior shoulder Posterior shoulder Medial epicondyle Lateral epicondyle Radial styloid Ulnar styloid 2nd MCP 5th MCP Index Thumb Trochanter	Static	Lower trunk Upper trunk Head Clavicle Upper arm Forearm Hand Thumb Index	Shoulder flexion/extension Elbow flexion/extension	Cardan-Euler / X-Y-Z	Yes

Authors	Type of Marker Set	Number of Markers	Location of Markers	Calibration Method	Segments	DoFs	LCS Definition / Rotation Sequence	ISB
Murgia et al. (2010)	Anatomical	11	Jugular notch C7 T10 Acromion Medial epicondyle Lateral epicondyle Radial styloid Ulnar styloid Base of 3rd MCP 2nd MCP 3rd MCP	NR	Trunk Upper arm Forearm Hand	Trunk flexion/extension Trunk lateral flexion Trunk axial rotation Shoulder plane of elevation Shoulder flexion/extension Shoulder internal/external rotation Elbow flexion/extension Elbow pronation/supination Wrist flexion/extension Wrist radial/ulnar deviation	Cardan-Euler /	Yes
Pereira et al. (2012)	Anatomical	14	Jugular notch Xiphoid process C7 T8 Acromion Medial epicondyle Lateral epicondyle Olecranon Radial styloid Ulnar styloid 2nd MCP 5th MCP Head of 3rd MCP	NR	Trunk Upper arm Ulna Radius Hand	Shoulder flexion/extension Shoulder abduction/adduction Shoulder internal/external rotation Elbow flexion/extension Elbow pronation/supination Wrist flexion/extension Wrist radial/ulnar deviation	Cardan-Euler / joint-specific	No
Petuskey et al. (2007)	Anatomical	18	Ears Head center C7 Sternum Acromion Lateral epicondyle Radial styloid Ulnar styloid Hand ASIS Sacrum	Static	Head Neck Pelvis Trunk Upper arm Forearm Hand	Trunk flexion/extension Trunk lateral flexion Trunk axial rotation Neck forward flexion Neck lateral flexion Neck rotation Shoulder flexion/extension Shoulder abduction/adduction Shoulder internal/external rotation Elbow flexion/extension Elbow pronation/supination Wrist flexion/extension Wrist radial/ulnar deviation	Cardan-Euler / X-Y-Z	No

Authors	Type of Marker Set	Number of Markers	Location of Markers	Calibration Method	Segments	DoFs	LCS Definition / Rotation Sequence	ISB
Qin et al. (2011)	Cluster	13	*3-marker cluster:* Thorax Upper arm Forearm Hand *Anatomical:* Index fingertip	Digitization	Trunk Upper arm Forearm Hand Finger	Shoulder flexion/extension Shoulder adduction/abduction Shoulder internal/external rotation Elbow flexion/extension Elbow pronation/supination Wrist flexion/extension Wrist radial/ulnar deviation MCP flexion/extension MCP abduction/adduction	NR	NR
Qin et al. (2014)	Cluster	12	*3-marker cluster:* Thorax Upper arm Forearm Hand *Digitization:* Xyphoid process Sternal notch C7 T8 Acromion Lateral epicondyle Medial epicondyle Radial styloid Ulnar styloid 2nd MCP 3rd MCP 5th MCP	Digitization	Trunk Upper arm Forearm Hand	Shoulder flexion/extension Shoulder adduction/abduction Shoulder internal/external rotation Elbow flexion/extension Elbow pronation/supination Wrist flexion/extension Wrist radial/ulnar deviation	Cardan-Euler / X-Y-Z	NR

Authors	Type of Marker Set	Number of Markers	Location of Markers	Calibration Method	Segments	DoFs	LCS Definition / Rotation Sequence	ISB
Rab et al. (2002)	Anatomical	18	Ears Head center Sternum C7 Acromion Lateral epicondyle Radial styloid Ulnar styloid Hand ASIS Sacrum	Static	Head Neck Pelvis Trunk Upper arm Forearm Hand	Shoulder flexion/extension Shoulder abduction/adduction Shoulder internal/external rotation Elbow flexion/extension	Cardan-Euler / X-Y-Z	No
Reid et al. (2010)	Cluster Anatomical	27	*3-marker clusters:* Upper arm Forearm *Anatomical:* Front head Back head Clavicular notch Sternum C7 Acromion Posterior shoulder Anterior shoulder Radial styloid Ulnar styloid 2nd CMC joint 5th CMC joint Head of 3rd MCP	Static	Head Trunk Upper arm Forearm Hand	Trunk flexion/extension Trunk lateral flexion Trunk axial rotation Shoulder flexion/extension Shoulder abduction/adduction Shoulder internal/external rotation Elbow flexion/extension Elbow supination/pronation Wrist flexion/extension Wrist radial/ulnar deviation	Cardan-Euler / X-Y-Z	Yes

Authors	Type of Marker Set	Number of Markers	Location of Markers	Calibration Method	Segments	DoFs	LCS Definition / Rotation Sequence	ISB
Ricci et al. (2015)	Anatomical	16	Clavicle Acromion Lateral epicondyle Medial epicondyle Radial styloid Ulnar styloid Thumb MCP Thumb PIP Distal end of thumb 2nd MCP 2nd PIP 2nd DIP 5th MCP 5th PIP 5th DIP	NR	Trunk Upper arm Forearm Hand	Shoulder flexion/extension Shoulder abduction/adduction Shoulder internal/external rotation Elbow flexion/extension Elbow pronation/supination Wrist flexion/extension Wrist radial/ulnar deviation	Cardan-Euler / X-Y-Z	Yes
Schmidt et al. (1999)	Cluster Anatomical	14	*3-marker cluster:* Upper arm Forearm Hand *Anatomical:* Acromion Lateral epicondyle Medial epicondyle Radial styloid Ulnar styloid	Static	Upper arm Forearm Hand	Elbow flexion/extension Elbow pronation/supination Wrist flexion/extension Wrist radial/ulnar deviation Wrist internal/external rotation	Cardan-Euler / Y-Z-X	NR

Authors	Type of Marker Set	Number of Markers	Location of Markers	Calibration Method	Segments	DoFs	LCS Definition / Rotation Sequence	ISB
van Andel et al. (2008)	Cluster	18	*3-marker cluster:* Thorax Acromion Hand *3-marker cuff:* Later upper arm *6-marker cuff:* Proximal to the ulnar and radial styloids *Digitization:* Xyphoid process Sternal notch C7 T8 Sternoclavicular notch Acromion Scapula inferior angle Scapula acromial angle Coracoid process Root of scapular spine Lateral epicondyle Medial epicondyle Radial styloid Ulnar styloid 3^{rd} MC 2^{nd} MCP 3^{rd} MCP 5^{th} MCP	Digitization	Trunk Scapula Upper Arm Forearm Hand	Scapula lateral rotation Shoulder elevation Shoulder internal/external rotation Elbow flexion/extension Elbow pronation/supination Wrist flexion/extension	Cardan-Euler	Yes

Authors	Type of Marker Set	Number of Markers	Location of Markers	Calibration Method	Segments	DoFs	LCS Definition / Rotation Sequence	ISB
Vanezis et al. (2015)	Cluster Anatomical	27	*3-marker cluster:* Acromion *4-marker cuff:* Later upper arm Forearm *Anatomical:* Forehead Backhead Xyphoid process Sternal notch C7 T8 Sternoclavicular notch Lateral epicondyle Medial epicondyle Radial styloid Ulnar styloid 2nd MCP 3rd MCP 5th MCP	Static	Head Trunk Scapula Upper Arm Forearm Hand	Head flexion/extension Head lateral flexion Head axial rotation Trunk flexion/extension Trunk lateral flexion Trunk rotation Scapular protraction/retraction Scapular medial rotation Scapular tilting Glenohumeral plane of elevation Glenohumeral elevation Glenohumeral rotation Shoulder plane of elevation Shoulder elevation Shoulder internal/external rotation Elbow flexion/extension Elbow pronation/supination Wrist flexion/extension Wrist ulnar/radial deviation	Cardan-Euler	Yes
Williams et al. (2006)	Cluster Anatomical	16	*3-marker cluster:* Upper arm Forearm Hand *Anatomical:* Acromion Lateral epicondyle Medial epicondyle Radial styloid Ulnar styloid	Static Functional	Trunk Clavicle Upper arm Forearm Hand	Sternoclavicular raising/lowering Sternoclavicular forwards/backwards Sternoclavicular rotation about long axis Shoulder flexion/extension Shoulder abduction/adduction Shoulder internal/external rotation Elbow flexion/extension Elbow pronation/supination	Cardan-Euler / Y-X-Z	NR

Authors	Type of Marker Set	Number of Markers	Location of Markers	Calibration Method	Segments	DoFs	LCS Definition / Rotation Sequence	ISB
Yang et al. (2002)	Cluster Anatomical	14	*3-marker cluster:* Upper arm Forearm Hand *Anatomical:* Acromion Later epicondyle Medial epicondyle Radial styloid Ulnar styloid	Static	Upper arm Forearm Hand	Shoulder flexion/extension Shoulder abduction/adduction Shoulder internal/external rotation Elbow flexion/extension Forearm pronation/supination Wrist flexion/extension Wrist radial/ulnar deviation	Cardan-Euler	NR

Table 3-4 Description of the functional tasks selected by the studies, kinematic outcomes reported, and motion capture system used.

Authors	Functional Tasks	Kinematic Outcomes	Motion Capture System (brand, # of cameras, sampling freq.)
Alt Murphy et al. (2006)	Drinking from a glass	Joint angle trajectories RoM Max velocity Time to completion Displacement trajectories Velocity graph Time to peak velocity Percent to peak velocity Angle vs. angle graph Inter-joint coordination	ProReflex Qualisys 3 240 Hz
Cimolin et al. (2012)	Arm motion during gait	Joint angle trajectories RoM Max/min joint angle Mean joint angle	ELITE2002 NR 100 Hz
Dennerlein et al. (2007)	Freestyle tapping Finger flexion/extension only tapping Wrist flexion/extension only tapping Elbow flexion/extension only tapping Shoulder motion only tapping	Joint angle trajectories RoM Resultant movement Joint contributions	Optotrak 3 200 Hz
Gates et al. (2016)	Box off shelf Box off ground Can off shelf Deodorant application Drinking from a cup Hand to back pocket Perineal care Donning and zipping pants	Joint angle trajectories Max joint angle	NR NR 120 Hz
Hebert et al. (2014)	Box and Blocks test	Joint angle trajectories RoM Max velocity Time to completion Displacement trajectories	Motion Analysis 8 60 Hz

Authors	Functional Tasks	Kinematic Outcomes	Motion Capture System (brand, # of cameras, sampling freq.)
Jaspers et al. (2011)	Reach forwards Reach sideways Reach upwards Reach grasp spherically Reach grasp vertically Reach grasp horizontally Hand to mouth Hand to top of head Hand to contralateral shoulder	Time to completion Mean velocity Joint angle at PTA	Vicon 12 100 Hz
Lobo-Prat et al. (2012)	Reaching task for nine target positions placed in front of the subject at three widths and three heights	Joint angle trajectories RoM Angular velocity vs. angular displacement graph Phase angle graph	BTS SMART-D® 6 140 Hz
Mugria et al. (2010)	Simulated page turning	Joint angle trajectories Joint ratio vs. joint ratio graph	Vicon 8 60 Hz
Pereira et al. (2012)	Turning a door knob Using a screwdriver Answering the telephone Feeding oneself with a spoon Taking a card from the shirt pocket and inserting it into a card slot	Joint angle trajectories RoM Angle vs. angle graph	Vicon 5 NR
Petuskey et al. (2007)	Hand to top of head High reach above head Hand to ipsilateral back pocket Forward reach to receive change Wave with arm at side, shoulder externally rotated	Joint angle trajectories RoM Joint angle at PTA	Motion Analysis 8 60 Hz
Qin et al. (2011)	Tapping on a single key Tapping left-right-left Tapping top-bottom-top	Joint angle trajectories RoM Resultant movement	Optotrak NR 200 Hz

Authors	Functional Tasks	Kinematic Outcomes	Motion Capture System (brand, # of cameras, sampling freq.)
Qin et al. (2014)	80-min simulated industrial assembly task involving repetitive reaching motions	Joint angle trajectories Mean joint angle	Optotrak NR 100 Hz
Rab et al. (2002)	Hand to top of head	Joint angle trajectories	NR
Reid et al. (2010)	Reach forwards to a low target Reach sideways to an elevated target Pronation/supination Hand to mouth	Joint angle time series	NR
Ricci et al. (2015)	"Pour water" task from the Elui Functional Test of the Upper Extremity	RoM	Vicon 8 200 Hz
Schmidt et al. (1999)	Plotter tracing 8-shaped curve with index finger	Joint angle trajectories	Vicon 5 50 Hz
van Andel et al. (2008)	Hand to mouth Hand to contralateral shoulder Combing hair Hand to back pocket Wrist flexion/extension Forearm pronation/supination Elbow flexion/extension Internal/external rotation with 90° humerus abduction Anterior flexion/extension Abduction/adduction	Joint angle trajectories RoM	Optotrak NR NR
Vanezis et al. (2015)	Reach upwards and grasp with horizontal grip Reach sideways and grasp with horizontal grip Reach forwards and grasp with horizontal grip Reach forwards and grasp with a vertical grip Hand to contralateral shoulder Hand to back head Hand to back pocket Drinking Throwing to a target	RoM Time to completion Mean velocity Index of curvature	Vicon 8 NR

Authors	Functional Tasks	Kinematic Outcomes	Motion Capture System (brand, # of cameras, sampling freq.)
Williams et al. (2006)	Removing a parking token	Joint angle trajectories	NR NR NR
Yang et al. (2002)	Target reaching task	Joint angle trajectories Displacement trajectories	Vicon 4 NR

3.4.2 Study Validity and Reliability

An adaptation of the Jerosch-Herold checklist for validity and reliability (Jerosch-Herold, 2005) is shown in Table 3-5. Item 2.a of the checklist focuses on the presence of a standardized protocol for administration. For a study to score positively on this measure, it must clearly describe the type and location of markers, type of calibration, selected segments and DoFs, and method for joint angle calculation. Thirteen studies included all these elements, therefore describing their protocol adequately for reproducibility (Gates et al., 2016; Hebert et al., 2014; Jaspers et al., 2011b; Lobo-Prat et al., 2012; Petuskey et al., 2007; Qin et al., 2014; Rab et al., 2002; Reid et al., 2010; Schmidt et al., 1999; van Andel et al., 2008; Vanezis et al., 2015; Williams et al., 2006; Yang et al., 2002). The last item in the Methods section pertains to sample size, with only one study performing a power calculation using a sample power of 90% (Ricci et al., 2015).

Table 3-5 Quality assessment of the selected studies using a checklist from Jerosch-Herold and adapted for the purposes of this review.

Authors	***Cimolin et al. (2012)***	***Dennerlein et al. (2007)***	***Gates et al. (2016)***	***Hebert et al. (2014)***	***Jasper et al. (2011)***	***Lobo-Prat et al. (2012)***	***Murgia et al. (2010)***	***Alt Murphy et al. (2006)***	***Pereira et al. (2012)***	***Petuskey et al. (2007)***	***Qin et al. (2011)***	***Qin et al. (2014)***	***Rab et al. (2002)***	***Reid et al. (2010)***	***Ricci et al. (2015)***	***Schmidt et al. (1999)***	***van Andel et al. (2008)***	***Vanezis et al. (2015)***	***Williams et al. (2006)***	***Yang et al. (2012)***
Methods																				
1. Is the purpose or the study clearly defined and focused on examining one or more measurement properties, that is, validity or reliability?	N	N	N	Y	Y	Y	N	Y	N	N	N	N	N	Y	N	N	N	Y	N	N
2.a Is there a standardized protocol for administration and scoring which is described fully?	N	N	Y	Y	Y	Y	N	N	N	Y	N	Y	Y	Y	N	Y	Y	Y	Y	Y
2.b Is the instrument described?	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	N	Y	Y	Y	Y	N	Y
3. Are the observers/testers appropriately trained or certified?	NR	NR	NR	NR	NR	NR	NR	NR	NR	Y	NR	NR	Y	NR	NR	Y	Y	NR	Y	NR
4. Were the data collected on an appropriate sample which is representative of the population to whom the measure will apply?	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
5. Is the sample size adequate? (Is there a power calculation?)	N	N	N	N	N	N	N	N	N	N	N	N	N	N	Y	N	N	N	N	N
Validity																				
6. Does the measure make intrinsic sense – face validity (expert opinion/consensus)?	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
7. Does the measure sample the content/domain adequately?	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
8. Is there evidence of the test's construct validity?	N	N	N	Y	N	N	N	N	N	N	N	N	Y	N	N	N	N	N	N	N
Reliability																				
9. Was test-retest reliability evaluated?	N	N	N	N	Y	N	N	Y	N	N	N	N	N	Y	N	N	N	Y	N	N
10. Was inter-tester reliability evaluated?	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N

The next two sections in the checklist relate specifically to validity and reliability. Several studies examined the validity or reliability of their kinematic data collection protocol (Alt Murphy et al., 2006; Hebert et al., 2014; Jaspers et al., 2011b; Lobo-Prat et al., 2012; Reid et al., 2010; Vanezis et al., 2015). When investigating construct validity, only two studies attempted to validate their protocols (Hebert et al., 2014; Rab et al., 2002). Rab et al. tested their model for algorithm accuracy and system stability using a rigid aluminum frame that could articulate in the same way as the shoulder girdle and upper extremity. From this analysis, they found that their protocol was rather unstable near regions of Gimbal lock when the shoulder was abducted to 90 degrees (Rab et al., 2002). Hebert et al. validated the kinematics for the modified Box and Blocks test when performed in a standing versus sitting position. While the authors found slight differences in the ranges of axial trunk rotation angle, anterior-posterior hand displacement, and medial-lateral sternum displacement between postures, they were not representative of the underlying kinematic trajectories. As such, it was concluded that the test could be administered in either a standing or sitting position (Hebert et al., 2014). Although this type of validation does not indicate whether the kinematic trajectories are valid when compared to a gold standard, it provides a form of cross-validation of the protocol.

The third section of the Jerosch-Herold checklist deals with the degree of reliability of a study. Intra-tester reliability was assessed in four studies (Alt Murphy et al., 2006; Jaspers et al., 2011b; Reid et al., 2010; Vanezis et al., 2015) Alt Murphy et al. assessed the consistency of their protocol by having six participants take off the retroreflective markers, leave the testing area for 5-10 minutes and come back to be tested again. They found that: (1) their measurements were within the 95% limits of agreement; (2) mean differences were close to zero; and (3) 95% confidence interval widths were narrow (Alt Murphy et al., 2006). Reid et al. had their participants return at least one week after initial testing for a second session, concluding that between-day repeatability was high (Reid et al., 2010). Jaspers et al. and Vanezis et al. tested their participants on two occasions, 2 to 10 days apart and one week apart, respectively (Jaspers et al., 2011b; Vanezis et al., 2015). Jaspers et al. assessed the reliability of temporal parameters and joint angles at the point of task achievement (PTA), which is defined as the instant when the movement extremum was reached, via the ICC coefficient as well as joint angle trajectories with the adjusted coefficient of multiple correlation (CMC) and measurement error. Their results indicated moderately high to very high between-session ICC for all tasks for movement duration and speed, high ICC for the scapula, shoulder, and elbow angles at PTA, but lower ICC for axial rotations. Lower between-session CMC were reported for joint angle trajectories in the transverse plane (Jaspers et al., 2011b). Vanezis et al. calculated the between-session standard error of measurement (SEM) for spatiotemporal parameters. For joint angle trajectories, they calculated CMC values and the measurement error. Spatiotemporal parameters showed low SEM values, and measurement errors for the joint angle trajectories were small across all tasks. Joint angle trajectories also showed good to excellent CMC values for most joints and all tasks. Joints with larger RoM displayed higher CMC values (Vanezis et al., 2015).

3.5 Discussion

This review aimed to evaluate previous work on upper body kinematics in non-disabled participants performing functional upper limb tasks. Since upper limb movements are highly variable, it is often difficult to compare kinematic outcomes across studies and tasks. Therefore, specific information from each selected study was extracted to create a synthesis of previous research. Thirteen studies clearly described the marker set characteristics, body segments and DoFs, as well as LCS definitions. This information allows adequate reproducibility of the motion capture protocols, a critical aspect for clinical implementation (Deschamps et al., 2011). A clear description of functional tasks analyzed was also provided, allowing for other sites to utilize the same tasks and, subsequently, cross-validate the kinematic outcomes. Furthermore, this review revealed that only a few studies have reported on the validity or reliability of their protocols (Alt Murphy et al., 2006; Hebert et al., 2014; Jaspers et al., 2011b; Rab et al., 2002; Reid et al., 2010; Vanezis et al., 2015).

3.5.1 Types of Upper Body Marker Sets

A majority of studies used a cluster marker set, either in combination with anatomical markers (Gates et al., 2016; Lobo-Prat et al., 2012; Reid et al., 2010; Schmidt et al., 1999; Vanezis et al., 2015; Williams et al., 2006; Yang et al., 2002), or by digitizing anatomical landmarks (Dennerlein et al., 2007; Jaspers et al., 2011b; Qin et al., 2014, 2011; van Andel et al., 2008). This is in contrast to the models often used in research involving impaired populations. Studies in individuals who have had a stroke (Alt Murphy et al., 2013, 2011; Kim et al., 2014; Lang et al., 2006, 2005), cerebral palsy (Chang et al., 2005; Klotz et al., 2013; Rönnqvist and Rösblad, 2007), or an upper limb amputation (Bertels et al., 2009; Cowley et al., 2016; Metzger et al., 2012) have all used anatomical marker sets for their kinematic protocols. Given this inconsistency, a focus of future studies should be on validating different types of upper body marker sets in various populations. Such work could provide evidence on which marker sets are more reliable with less occlusion for a given functional task, and lead to stronger evidence to recommend a specific marker sets.

3.5.2 Degrees of Freedom

The studies in this review reported adequately on shoulder, elbow, and wrist DoFs. However, only seven studies examined trunk kinematics (Gates et al., 2016; Hebert et al., 2014; Jaspers et al., 2011b; Murgia et al., 2010; Petuskey et al., 2007; Reid et al., 2010; Vanezis et al., 2015). When upper limb function has been compromised, movement compensation can occur, with the remaining sound joints and trunk substituting for the motion of impaired joints (Levin et al., 2008). For example, a study by Robertson and Roby-Brami assessed trunk motion during a seated reaching task in non-disabled individuals and individuals who had suffered a stroke. Their results revealed that trunk flexion and trunk torsion were greater in stroke survivors than in non-disabled individuals (Robertson and Roby-Brami, 2011). In upper limb prosthesis use, trunk compensation has been shown to be a key compensatory strategy to accomplish a functional movement task (Hebert and Lewicke, 2012). As compensatory movements have been linked to increased risks of injury (Chorba et al., 2010), ideally the respective DOFs (e.g., of the trunk) are adequately characterized in normative studies. While non-disabled individuals may not present with any compensatory movements for a given task, underlying data can be used as a benchmark for quantifying compensation in impaired populations.

3.5.3 Conventions for Calculating Joint Angles

The ISB has developed guidelines to standardize LCS definitions when conducting kinematic analyses (Wu et al., 2005), and researchers have been encouraged to follow these guidelines to improve standardization and reproducibility (Kontaxis et al., 2009). Eight studies in this review followed the ISB guidelines (Gates et al., 2016; Jaspers et al., 2011b; Lobo-Prat et al., 2012; Murgia et al., 2010; Reid et al., 2010; Ricci et al., 2015; van Andel et al., 2008; Vanezis et al., 2015). Selected other studies (Cimolin et al., 2012; Pereira et al., 2012; Petuskey et al., 2007; Rab et al., 2002) used rotation sequences that they described as being more clinically relevant, similar to those used in lower limb kinematic analysis. The method used by these studies applied a sequential rotation about three orthogonal axes in the X-Y-Z order to obtain flexion/extension, abduction/adduction, and axial rotation (Rab et al., 2002).

Determining the kinematics of the humerus relative to the thorax requires additional considerations when selecting the rotation sequence. The Y-X-Y rotation sequence recommended by ISB can result in Gimbal lock, specifically during tasks that require the upper arm to be elevated with an angle of close to 180 degrees (Doorenbosch et al., 2003; Kontaxis et al., 2009), such as reaching for an object on a shelf at head height (Gates et al., 2016) or when performing a hand-to-head task (Rab et al., 2002). Several studies have explored different shoulder rotation sequences to investigate if an alternate sequence would decrease the incidence of Gimbal lock (Bonnefoy-Mazure et al., 2010; Senk and Cheze, 2006). Bonnefoy-Mazure et al. compared three rotation sequences, Y-X-Y (ISB recommendation for the shoulder), Z-X-Y (ISB recommendation for most other joints), and X-Z-Y (alternate rotation sequence used in previous studies). Of these, X-Z-Y was found to not result in Gimbal lock for elite tennis players' flat serve (Bonnefoy-Mazure et al., 2010). The authors therefore recommended that the rotation sequence should be selected based on the task being analyzed (Bonnefoy-Mazure et al., 2010). Senk and Cheze recommended that the ISB-recommended sequence Y-X-Y be used for the shoulder complex when movements do not pass through a singular position and do not reach a maximum position; this has the added benefit of calculating accurate angles when movements are performed outside of an anatomical plane (Senk and Cheze, 2006). Regardless of whether the studies chose to follow ISB guidelines, most studies reported their method for calculating joint angles, which is essential to ensure reproducibility of the protocol.

3.5.4 Functional Upper Limb Tasks

When selecting functional tasks, it is important that they are reproducible and relevant to the particular population being studied. It has been suggested that, due to the wide range of possible movement strategies and large RoM of the upper limb, selected tasks should be goal-oriented and standardized to allow for ease of comparison between trials and individuals (Kim et al., 2014). Goal-oriented tasks are those that have an end goal and a high task specificity, such as drinking from a cup. Although this particular task is a complex upper extremity task, it has a cyclical motion that can be subdivided into different phases, facilitating kinematic analysis (Alt Murphy et al., 2006; Gates et al., 2016; Kim et al., 2014; Vanezis et al., 2015). Other tasks have been modified from traditional clinical assessments, such as the modified Blocks and Box task used by Hebert et al. In this task, the blocks were placed in specific locations within the box, and participants were required to move the blocks in a specific order to maintain a cyclical motion conducive to kinematic analysis (Hebert et al., 2014). Most tasks selected by the reported studies were goal-oriented and could be subdivided into smaller phases for kinematic analysis. Standardized goal-oriented tasks also improve the ability to compare between trials or sessions, and are therefore often suitable for documenting change with therapeutic intervention (De Los Reyes-Guzmán et al., 2014).

Task selection can also be based on common protocols used in prior kinematic studies, specifically to study reliability or to compare impaired performance against a normative benchmark. For example, the task of drinking from a cup has been commonly reported both in non-disabled populations (Alt Murphy et al., 2006; Gates et al., 2016; Vanezis et al., 2015) and those with upper limb impairments (Alt Murphy et al., 2013, 2011; Butler et al., 2010; Kim et al., 2014). This task is goal-oriented and standardized, which is beneficial for kinematic analysis, while also including features that might be challenging for impaired populations, e.g., transporting the cup to the mouth. The level of risk of this task can be varied by using a flexible cup, which requires accurate grasp force modulation. Furthermore, that flexible cup can be filled with water, which further increases the level of risk of the task (Latash and Jaric, 2002). Other commonly used tasks in the literature involved reaching for an object or target, and reaching for and grasping an object (Cacho et al., 2011; Chang et al., 2005; Jaspers et al., 2011b; Lang et al., 2006, 2005; Lobo-Prat et al., 2012; Reid et al., 2010; Rönnqvist and Rösblad, 2007; Vanezis et al., 2015; Yang et al., 2002). It is important to note that the goal of the task (e.g., simple reaching versus reaching and moving an object in a goal-oriented way) may change the execution of the task (Valyear et al., 2011). Therefore, consideration should be given to choosing functional, goal-oriented tasks that have greater applicability across normative and impaired populations.

3.5.5 Kinematic Outcomes

A number of kinematic outcomes were presented in the reviewed studies. Data were presented via several graphical visualizations, ranging from joint angle trajectories to angle versus angle graphs (Alt Murphy et al., 2006; Pereira et al., 2012). Numerical data were also presented, with RoM being the most common measure extracted. RoM can be a useful measure to assess functional requirements necessary for ADLs, and is a frequently used measure at the start of a therapeutic intervention since it allows therapists to assess the abilities of their patients (Gates et al., 2016). A recent review found, however, that RoM was not the most commonly reported measure in studies assessing upper extremity kinematics in individuals post-stroke. Instead, peak and mean velocity as well as movement smoothness were more frequently used (Alt Murphy and Häger, 2015). From the studies reviewed here, only four studies reported velocity or smoothness measures (Alt Murphy et al., 2006; Hebert et al., 2014; Jaspers et al., 2011b; Vanezis et al., 2015). Future studies assessing non-disabled participants should consider kinematic measures that are of specific interest in impaired populations to create a database for comparison. Another option would be to make the kinematic source data, such as the kinematic time series, available as a supplement or in a repository. This would allow researchers interested in different population-specific outcomes to extract relevant outcomes from a non-disabled data set.

Novel kinematic measures should be explored and further evaluated in future studies. One example is the Pediatric Upper Limb Temporal-Spatial Equation (PULTSE), which is a measure that results from a multivariate logistic regression incorporating several different temporal-spatial kinematic parameters. This measure provides information on the neuromuscular deficiencies that may be present in an individual. The five temporal-spatial parameters used in PULTSE are movement time, number of movement units, angular velocity, index of curvature, and ratio between peak velocity during transport and peak velocity during reach (Butler and Rose, 2012). Kinematic measures such as PULTSE could be of practical value in future work assessing the overall effect of an intervention on upper body movement – since they synthesize several kinematic parameters into a single score. To be of most value, these types of composite measures should also provide access to source data, to ensure accurate comparison in future studies. Derived kinematic information could be used for more tailored analyses and for selecting different therapeutic interventions.

3.5.6 Validity and Reliability of Kinematic Protocols

Only a few studies specifically assessed the validity and reliability of the protocol used. Evaluating construct validity when using an optical motion capture system is not an easy task considering that the gold standard for this technique is using bone pins (Cappozzo et al., 1995) or fluoroscopy (Hurschler et al., 2009). Bone pins are highly invasive, costly, and labor intensive. Fluoroscopy faces similar challenges while also requiring doses of radiation. Both techniques have been used for various joints of the body, including the shoulder (Dal Maso et al., 2016; Millett et al., 2016), knee (Nakamura et al., 2015; Reinschmidt et al., 1997), ankle (Wang et al., 2015; Westblad et al., 2002), and foot (Lundgren et al., 2008; Shultz et al., 2011); however, application is lacking for the entire upper limb kinematic chain. Less precise measures based on goniometer measurements have also been used to establish the validity of a motion capture protocol (Rettig et al., 2009). Additional validation could be pursued by directly comparing different types of marker sets (cross-validation). This type of comparison has been done for the lower limbs where Collins et al. compared gait kinematics for a conventional anatomical marker set to those for a combined anatomical and cluster marker set, concluding that results were comparable (Collins et al., 2009). A similar cross-validation study comparing a cluster maker set (most commonly used when assessing non-disabled individuals) with a conventional anatomical marker set (commonly used in impaired populations) would improve the understanding of the validity of these approaches for upper limb kinematic analyses.

Reliability tests are relatively easy to conduct and should be included in studies that produce new protocols for kinematic analysis. Only four studies in this review assessed intra-tester reliability (Alt Murphy et al., 2006; Jaspers et al., 2011b; Reid et al., 2010; Vanezis et al., 2015) using mean differences, the 95% limits of agreement, ICC, CMC, and SEM. Overall, these studies found their protocols to have good reliability, and their results are consistent with other studies that reproduced their own protocols in children with cerebral palsy (Schneiberg et al., 2010). It should be stressed that inter-tester reliability has not been assessed to the same extent as intra-tester reliability, which is a concern given that the placement of markers is well-known to be prone to error across administrators. Recently, Leigh et al. evaluated inter-tester reliability for gait by comparing kinematics collected by a biomechanist with eight years of experience against those collected by a clinician with no motion analysis experience. The results showed that, after four sessions of training, an initially untrained clinician is as reliable as an experienced tester (Leigh et al., 2014). While these results from lower limb motion capture are promising, similar reliability efforts are needed for the upper body to assess the effect of administrator experience on kinematic outcomes.

As motion capture technologies and the field of upper body kinematic analysis advance, accurate reporting of protocols becomes more crucial. Four studies failed to report the type of motion capture system used (Gates et al., 2016; Rab et al., 2002; Reid et al., 2010; Williams et al., 2006). Importantly, the lack of full reporting was mostly observed in specifics such as the calibration method (Alt Murphy et al., 2006; Cimolin et al., 2012; Dennerlein et al., 2007; Murgia et al., 2010; Pereira et al., 2012; Ricci et al., 2015) and LCS definition used (Alt Murphy et al., 2006; Dennerlein et al., 2007; Qin et al., 2011). Validity and reliability of the protocols were not reported in most studies. Future studies should standardly report the validity and reliability of their kinematic protocols, since these are key factors to allow accurate replication of experimental protocols.

3.6 Conclusion

This review discussed the available protocols and kinematic outcomes when quantifying upper body kinematics during upper limb tasks using optical motion capture. Twenty studies met the inclusion criteria, presenting normative data on a variety of upper limb tasks. Kinematic model characteristics were generally well described, but there was a clear divide in terms of following ISB standardization procedures for upper limb kinematics, as less than half of the included studies adhered to certain aspects of those guidelines. Most studies did not assess trunk kinematics, which should be considered in future studies, specifically to allow comparison of compensatory movements in impaired populations. Various kinematic models have been used, but have not been extensively assessed for validity and reliability. Future studies should aim to determine a standardized upper body kinematic model that shows high validity and reliability in non-disabled individuals, prior to being used in populations with upper limb impairments.

3.7 References

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Chapter 4. Characterization of Normative Hand Movements During Two Functional Upper Limb Tasks

The material presented in this chapter has been published in the article:

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The content of this chapter is identical to the material presented in the publication, except for the text formatting which was done according to University of Alberta requirements. Parts of this work have also been presented at scientific conferences including *The 40th Annual Meeting of the American Society of Biomechanics,* held on August 2 to August 5, 2016, in Raleigh, North Carolina, United States, and *The Spotlight on Research Breakfast*, held on October 20, 2016, in Edmonton, Canada.

4.1 Abstract

Background: Dexterous hand function is crucial for completing ADLs, which typically require precise hand-object interactions. Kinematic analyses of hand trajectory, hand velocity, and grip aperture provide valuable mechanistic insights into task performance, but there is a need for standardized tasks representative of ADLs that are amenable to motion capture and show consistent performance in non-disabled individuals. Our objective was to develop two standardized functional upper limb tasks and to quantitatively characterize the kinematics of normative hand movement.

Methods: Twenty non-disabled participants were recruited to perform two tasks: the Pasta Box Task and Cup Transfer Task. A 12-camera motion capture system was used to collect kinematic data from which hand movement and grip aperture measures were calculated. Measures reported for reach-grasp and transport-release segments were hand distance travelled, hand trajectory variability, movement time, peak and percent-to-peak hand velocity, number of movement units, peak and percent-to-peak grip aperture, and percent-to-peak hand deceleration. A between-session repeatability analysis was conducted on 10 participants.

Results: Movement times were longer for transport-release compared to reach-grasp for every movement. Hand and grip aperture measures had low variability, with 55 out of 63 measures showing good repeatability (ICC > 0.75). Cross-body movements in the Pasta Box Task had longer movement times and reduced percent-to-peak hand velocity values. The Cup Transfer Task showed decoupling of peak grip aperture and peak hand deceleration for all movements. Movements requiring the clearing of an obstacle while transporting an object displayed a double velocity peak and typically a longer deceleration phase.

Discussion: Normative hand kinematics for two standardized functional tasks challenging various aspects of hand-object interactions important for ADLs showed excellent repeatability. The consistency in normative task performance across a variety of task demands shows promise as a potential outcome assessment for populations with upper limb impairment.

4.2 Introduction

Dexterous hand function is essential for successfully performing many ADLs. Neurological or musculoskeletal impairments such as stroke (Lang et al., 2005), spinal cord injury (Mateo et al., 2015), and upper limb amputation (Hebert and Lewicke, 2012; Metzger et al., 2012) result in deficiencies in hand and upper limb function, such that alternate control strategies and compensations must be used to accomplish ADLs. A key aspect of ADLs are hand-object interactions, where successfully reaching, grasping, and transferring an object is crucial for task completion. Quantifying these hand-object interactions in non-disabled populations to allow comparison to strategies used by impaired individuals could provide a valuable tool for assessing hand function.

One method of examining hand-object interactions is through kinematic analysis using optical motion capture, either to measure joint angles of the full upper body kinematic chain to infer hand function, or to directly quantify hand function through specific features of how the hand moves (De Los Reyes-Guzmán et al., 2014). However, the design of the object interaction task becomes crucial in developing a standard assessment protocol that is repeatable and reliable for comparison within a normative population and across impaired populations. Specifically, hand movement during object interactions is influenced by an object's extrinsic (location and orientation) and intrinsic parameters (size, color, shape, mass, and texture) (Cuijpers, 2004; Smeets and Brenner, 1999). When reaching for objects, normative adult behaviour will show typical hand trajectories, hand velocities, and grip aperture motions (Abend et al., 1982; Cuijpers, 2004; Jeannerod, 1984). Reaching is influenced by the object's extrinsic parameters, and typically characterized by a straight or gently curved hand trajectory path from an initial hand position to the object (Abend et al., 1982), with a smooth bell-shaped velocity profile with one velocity peak occurring approximately halfway through the movement (Jeannerod, 1984), and with greater peak hand velocities observed for targets that are further away (Gordon et al., 1994). Grasp is primarily influenced by intrinsic parameters (Smeets and Brenner, 1999) and characterized by hand pre-shaping at hand movement onset (Cuijpers, 2004), with grip aperture (the distance between the thumb and index finger) reaching a maximum at approximately 60 to 70% of the reaching phase, followed by hand closing around the object (Jeannerod, 1984). Grip aperture is also a function of object size, where a larger grip aperture is required for larger objects (Jeannerod, 1984; Smeets and Brenner, 1999).

Given the importance of object interactions in ADLs and the influence of an object's intrinsic and extrinsic proprieties on hand movement, task selection for kinematic analysis should include ecologically valid tasks for clinical assessment. Although some upper limb kinematic assessment protocols for motion capture mimic functional movements, such as hand to head (e.g., for combing hair), hand to shoulder (e.g., for dressing, applying deodorant), and hand to back pocket (e.g., for reaching for wallet, perineal care) (Gates et al., 2016; Jaspers et al., 2011b; Petuskey et al., 2007; van Andel et al., 2008; Vanezis et al., 2015), they provide limited information on hand function during real object interactions. In clinical populations, reaching and grasping tasks using real objects have shown alterations in hand kinematics such as asymmetries in hand velocity profile and decoupling of reach and grasp in those with hemiparesis (Lang et al., 2005; Schaefer et al., 2012; van Vliet and Sheridan, 2007), spinal cord injury (Mateo et al., 2015) and with use of a prosthesis (Bouwsema et al., 2010). These studies have used a variety of objects for grasping such as a cup (van Vliet and Sheridan, 2007), ball (Lang et al., 2005), or cylinder (Bouwsema et al., 2010; Lang et al., 2005; Schaefer et al., 2012). However, it has been shown that not only the object characteristics but also the goal of the object interaction will affect grasp kinematics (Valyear et al., 2011). Therefore, a standardized functional task protocol for kinematic assessment with applicability to clinical populations would ideally involve reaching and grasping real objects, with specific movement goals, in order to most accurately mimic typical daily tasks.

Clinical assessments currently exist that evaluate hand function involving hand-object interactions. Performance tests, such as the Jebsen Test of Hand Function (Jebsen et al., 1969), the Box and Blocks Test (Jongbloed-Pereboom et al., 2013), and Standardized Object Test (Thrope et al., 1989), as well as subjective rater tests, such as the Action Research Arm Test (Lyle, 1981) and Assessment of Capacity of Myoelectric Control (ACMC) (Lindner et al., 2009) are commonly administered in a clinical environment. Although these tests involve hand-object interactions and provide a global outcome measurement of function, they do not allow for precise quantitative assessment of grasp, dexterity, movement quality, and efficiency. Ideally, functional assessment tasks used for kinematic analysis would utilize elements of these current clinical assessments, such as moving the arm in different positions; lateral reaches; crossing the body's midline; adjusting hand opening and closing; varying grasp patterns; modulating force when gripping; and grasping and releasing objects.

The objectives of this study were to develop two standardized functional upper limb tasks with hand-object interactions that result in consistent and repeatable performance in non-disabled individuals, and to use kinematic analysis to quantitatively characterize hand movement for those two tasks. The hypothesis was that the performance of the tasks in non-disabled individuals would result in consistent performance (low variability) within and across performers and good between-session repeatability due to the standardized sequencing of the task movements.

4.3 Methods

4.3.1 Functional Task Development

The tasks were developed through iteration and consensus by a team involving a movement neuroscientist, kinesiologist, physiatrist, and occupational therapist. Current best-practice outcome measures for upper limb function were explored for commonalities in task requirements (Hebert et al., 2014; Hudak et al., 1996; Jebsen et al., 1969; Jongbloed-Pereboom et al., 2013; Lindner et al., 2009; Resnik et al., 2013a). Functional tasks incorporated elements that would be challenging, but not impossible for clinical populations to complete, while being representative of 'real-world' tasks that might be performed in anyone's daily environment. A key feature of the tasks was that they needed to be amenable to motion capture with standardized, discrete movement sequences to optimize kinematic analysis of hand movement characteristics across performers. Specifically, standardization of order of task execution allows kinematic data segmentation into specific movement sequences that can be averaged across trials and individuals to isolate characteristic movement strategies.

Two standardized functional tasks were developed, the Pasta Box Task and Cup Transfer Task (Figure 4-1). Full task set up and descriptions are available in the supplementary materials. The Pasta Box Task (Appendix B) was designed to mimic moving objects from a counter to a cupboard, between cupboards at different heights, and across the body's midline. The Pasta Box Task consisted of three movements, during which the performer moved a box of pasta from a lower side shelf on their right (height: 30 inches) to a shelf in front of them (height: 43 inches); then to a second shelf at a higher height across the body (height: 48 inches); and then back to the starting position. The performer was required to return the hand to a "home" position after each specified movement. The Cup Transfer Task (Appendix C) was designed to involve greater risk by using compliant cups with content that can be spilled, and requiring careful placement around barriers such as would be encountered at a sink or countertop. The Cup Transfer Task consisted of four movements, where the performer moved two compliant cups filled with therapeutic beads from an initial position on the right side of a box to specific target positions on the left side of the box, and then back again to the start locations, while having to clear a middle partition. The box was placed at a standard counter height of 36 inches to recreate a real-world environment. The performer was required to return the hand to a "home" position after the first two movements and at the end of the task. In order to challenge grasp capabilities which might be difficult for impaired populations, two types of grasps, linked to the placement of the cups in the box, were required: a top grasp for the near cup and a side grasp for the far cup.

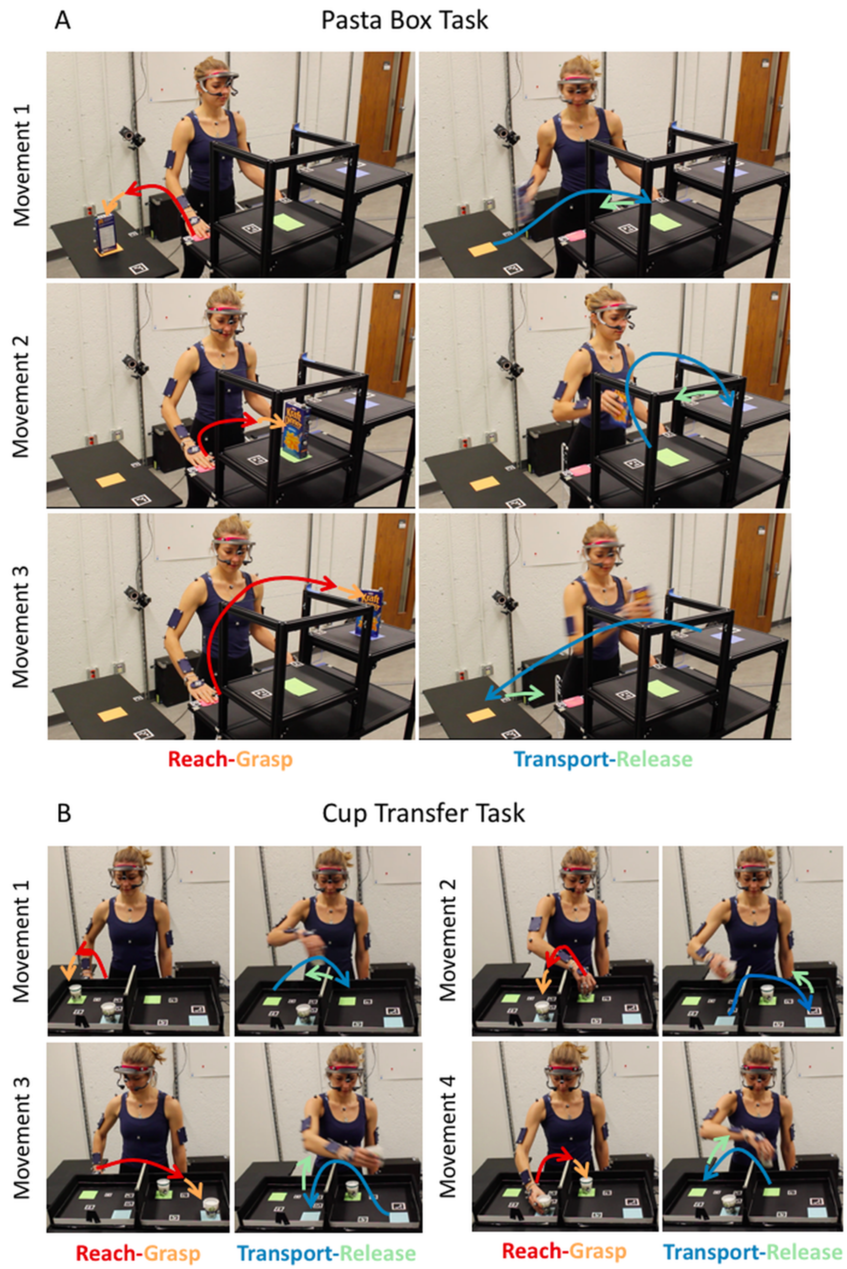

Figure 4-1 Sequence of the Pasta Box Task (A) and Cup Transfer Task (B). During the Pasta Box Task, the participant moved the box of pasta from a lower side table to two shelves of different heights in front of them (Movements 1 and 2) and back again to the start position (Movement 3). Tasks were completed using three distinct movements, with standardized placement positions, including returning the hand to a standard "home" position at the end of each movement. During the Cup Transfer Task, the participant moved two compliant cups filled with therapeutic beads over a partition to a target location using a top grasp for the first cup and a side grasp for the second cup (Movements 1 and 2). These movements were followed by a return of the hand to the "home" position, and then by moving the cups back to their initial positions using respective types of grasps (Movements 3 and 4).

4.3.2 Study Participants

Twenty non-disabled individuals (11 male; 18 right-handed; age: 25.8 ± 7.2 years; height: 173.8 ± 8.3 cm; mean ± standard deviation) were recruited to participate in the study. They had no upper body pathology or history of neurological or musculoskeletal injuries within the past two years. The study followed the Declaration of Helsinki guidelines and was approved by the University of Alberta Health Research Ethics Board (Pro00054011), the Department of the Navy Human Research Protection Program (DON-HRPP), and the SSC-Pacific Human Research Protection Office (SSCPAC HRPO). The individual in Figure 4-1 has provided written consent to publish the photographs.

4.3.3 Experimental Setup and Procedures

A 12-camera Vicon Bonita motion capture system (Vicon Motion Systems Ltd, Oxford, UK) with an accuracy of 0.5 mm and 0.5 degrees was used to collect 3D marker trajectories at 120 Hz. A rigid plate with three 11.1 mm reflective markers was attached to the dorsal side of the right hand using double-sided tape. Two 14 mm single reflective markers were attached to the middle phalange of the index finger and the distal phalange of the thumb. Additional markers and marker clusters were attached to upper body segments (pelvis; trunk; upper arms; forearms; head), but were not used in the current analysis.

Prior to data collection, each participant received verbal instructions, a demonstration, and a practice trial to be familiarized with the tasks. Each participant performed a minimum of 20 successful trials for both tasks. If there was an error in performance of the task (i.e., dropping the object), that trial was marked as an "error trial" and the trial was repeated until a total of 20 error-free trials were recorded. The order of the tasks was block-randomized, with ten participants starting with the Pasta Box Task and ten with the Cup Transfer Task. Ten participants returned on a separate day for repeatability testing after the initial testing session (7.5 months ± 11 days), with the identical set up. The same two testers ran all data collection sessions.

4.3.4 Experimental Data Analysis

Raw marker trajectory data were filtered using a second-order, low-pass Butterworth filter with a cut-off frequency of 6 Hz (Winter, 1979). Motion capture data were segmented based on hand velocity, object velocity, and grip aperture (Table 4-1). The Pasta Box Task was divided into three movements, and the Cup Transfer Task was divided into four movements. Each task had a standard starting position for the hand (labelled 'home'). Participants had to bring their hand to the "home" position after each movement for the Pasta Box Task and after the first two movements of the Cup Transfer Task to allow for task segmentation and standardization. Each movement was composed of four phases: reach, grasp, transport, and release. For the quantitative kinematic analysis, due to the short duration of grasp and release phases, and to interpret the results in light of functional hand movement sequences, the reach and grasp phases were combined into a reach-grasp segment, and the transport and release phases into a transport-release segment.

Table 4-1 Segmentation and phase definitions. Phase start and end definitions for the two functional tasks. Each task movement is separated into four phases: reach, grasp, transport, and release. The start and end of the phases are based on kinematic variables of hand velocity, object velocity, grip aperture, and hand-to-target or object-to-target distance. 'Hand Velocity Threshold' was defined as 5% of the peak hand velocity during the trial. 'Object Velocity Threshold' was defined as 5% of the peak object velocity during the trial. 'Grasp Distance Threshold' and 'Release Distance Threshold' were based on average occurrence of peak grip aperture prior to and following object movement, respectively. 'Target Distance Threshold' was defined as the location of the hand or object during a transition phase with respect to the target plus a tolerable distance of 70 mm.

Phase Name	Start/End	Definition
Reach	**Start:** Hand leaves the home position	First occurrence of the hand exceeding the 'Hand Velocity Threshold' OR first occurrence of the hand exceeding the 'Target Distance Threshold', whichever happens first
Grasp	**Start:** Closing of grip aperture	First occurrence of the hand falling below the 'Grasp Distance Threshold'
Transport	**Start:** Start of object movement	First occurrence of the object exceeding the 'Object Velocity Threshold' OR first occurrence of the object exceeding the 'Target Distance Threshold', whichever happens first
Release	**Start:** End of object movement	First occurrence of the object falling below the 'Object Velocity Threshold' OR first occurrence of the object distance falling below the 'Target Distance Threshold', whichever happens last
	End: End of grip aperture opening	Last occurrence of the hand before exceeding the 'Release Distance Threshold'

Kinematic measures were selected based on commonly reported measures in assessments of individuals with upper limb impairments (Alt Murphy and Häger, 2015; De Los Reyes-Guzmán et al., 2014). Hand movement was calculated using the average position of the three markers on the hand plate. Grip aperture was defined as the distance between the markers attached to the index and thumb. Analysed measures were movement time, hand distance travelled, hand trajectory variability, peak hand velocity, percent-to-peak hand velocity, number of movement units, peak grip aperture, percent-to-peak grip aperture, and percent-to-peak hand deceleration. Percent-to-peak measures were defined as the percent of time elapsed before the peak for a specific reach-grasp or transport-release segment. Hand trajectory variability was quantified as the maximum of the mean 3D standard deviation at each time-normalized point. Number of movement units was defined as a local maximum velocity, or velocity peak (Alt Murphy et al., 2011; Cirstea et al., 2003; Schneiberg et al., 2010) of the hand and was calculated by finding the zero-crossings in the hand acceleration profile where the signal switches from positive to negative. The hand trajectory, hand velocity, and grip aperture time series were time-normalized by segment (resampled to have 100 points per segment), averaged across trials and participants for each segment, and resampled across segments based on average segment length (with 1,000 points per overall trial).

4.3.5 Statistical Analysis

Statistical analysis was completed using the SPSS software (IBM Corporation, Armonk, NY, USA). For each task, hand trajectory variability, movement time, peak hand velocity and percent-to-peak hand velocity were analyzed using a two-way repeated-measures analysis of variance (ANOVA) examining effects of movement (3 for Pasta, 4 for Cups) and segment (reach-grasp, transport-release). Significant interactions ($p < 0.05$) were examined by conducting simple main effect one-way repeated-measures ANOVA's of movement at each level of segment. Significant main or simple main effects ($p < 0.05$) were followed up by conducting all pairwise comparisons with Bonferroni correction. Normality was assessed using the Kolmogorov-Smirnov Test and sphericity was assessed through a Mauchly's Test of Sphericity. In cases where the assumption of sphericity was not met, a Greenhouse-Geisser Correction was applied and reported. For peak grip aperture, percent-to-peak grip aperture, and percent-to-peak hand deceleration a one-way repeated-measures ANOVA, with Bonferroni corrected pairwise comparisons where significant ($p < 0.05$), was conducted to assess potential differences between movements for the reach-grasp segment only.

A between-session repeatability analysis was performed by calculating the ICC for model (2,k), the SEM, and the minimal detectable change (MDC) (Portney and Watkins, 2009) between the first and second session for ten participants. SEM was calculated based on the ICC analysis scores. The equation for SEM was:

$$SEM = SD\sqrt{1 - ICC} \quad (1)$$

where SD is the standard deviation of all the participants in the first session. The MDC was calculated based on the SEM values and the 95% confidence interval. The equation for MDC was:

$$MDC = SEM \times 1.96 \times \sqrt{2} \quad (2)$$

where 1.96 is the z score associated with the 95% confidence interval (Weir, 2005). SEM and MDC scores were also represented as a percentage of the absolute average measurement value to indicate relative error. ICC, SEM, and MDC values were calculated for movement time, peak hand velocity, percent-to-peak hand velocity, peak grip aperture, percent-to-peak grip aperture, and percent-to-peak hand deceleration. ICC values above 0.90 were considered to indicate reasonable reliability for clinical measurements, above 0.75 indicated good repeatability, and below 0.75 indicated poor to moderate repeatability (Portney and Watkins, 2009).

4.4 Results

4.4.1 Task Performance

Overall performance time (from start to finish) for the Pasta Box Task was 8.84 ± 0.34 seconds, and for the Cup Transfer Task 10.60 ± 0.49 seconds. Error trials occurred at a rate of 4% for the Pasta Box Task, and 11% for the Cups Transfer Task. The most common errors were sequence hesitation (Pasta Box Task: 38% of errors, Cup Transfer Task: 54% of errors), hitting a partition/obstacle (Pasta Box Task: 31% of errors, Cup Transfer Task: 25% of errors), and incorrect grasp of the object (Pasta Box Task: 12% of errors, Cup Transfer Task: 16% of errors).

Movement times, hand distance travelled, and hand trajectory variability for each movement are listed in Tables 4-2 and 4-3 for the Pasta Box Task and Cup Transfer Task, respectively. Statistical results including post-hoc pairwise comparisons are presented in Tables 4-4 and 4-5 for the Pasta

Box Task and Cup Transfer Task, respectively, and discussed below in the relevant sections per task.

Table 4-2 Pasta Box Task Kinematic Measures. Pasta Box Task measures for hand distance travelled, hand trajectory variability, movement time, peak hand velocity, percent-to-peak hand velocity, number of movement units, peak grip aperture, percent-to-peak grip aperture, and percent-to-peak hand deceleration. Data are presented, for movements and segments separately, as group means and across-participant standard deviations (SD). Average within-participant variability (WPV) is also presented for each measure. Movements are: Movement 1 (Mvmt 1), Movement 2 (Mvmt 2), and Movement 3 (Mvmt 3); segments are: reach-grasp (RG) and transport-release (TR).

		Hand distance travelled (mm)		**Hand trajectory variability (mm)**	**Movement time (sec)**	
		Mean ± SD	*WPV*	*Mean ± SD*	*Mean ± SD*	*WPV*
Mvmt 1	RG	464 ± 25	21	17 ± 5	0.97 ± 0.15	0.07
	TR	850 ± 27	14	19 ± 3	1.36 ± 0.16	0.07
Mvmt 2	RG	478 ± 21	12	13 ± 3	0.68 ± 0.11	0.05
	TR	740 ± 72	23	19 ± 4	1.45 ± 0.18	0.08
Mvmt 3	RG	701 ± 21	14	19 ± 4	0.84 ± 0.15	0.05
	TR	1069 ± 22	16	32 ± 6	1.68 ± 0.24	0.10

		Peak hand velocity (mm/s)		**Percent-to-peak hand velocity (%)**		**Number of movement units**	
		Mean ± SD	*WPV*	*Mean ± SD*	*WPV*	*Mean ± SD*	*WPV*
Mvmt 1	RG	1007 ± 125	71	42.5 ± 4.0	2.9	1.2 ± 0.3	0.3
	TR	1330 ± 140	69	33.1 ± 3.7	4.0	1.3 ± 0.3	0.5
Mvmt 2	RG	1204 ± 151	54	43.2 ± 6.5	3.8	1.1 ± 0.1	0.2
	TR	1035 ± 114	52	45.8 ± 5.7	8.5	2.3 ± 0.3	0.4
Mvmt 3	RG	1466 ± 197	74	38.8 ± 5.2	4.9	1.2 ± 0.2	0.3
	TR	1470 ± 164	94	32.5 ± 3.8	3.6	1.8 ± 0.5	0.9

		Peak grip aperture (mm)		**Percent-to-peak grip aperture (%)**		**Percent-to-peak hand deceleration (%)**	
		Mean ± SD	*WPV*	*Mean ± SD*	*WPV*	*Mean ± SD*	*WPV*
Mvmt 1	RG	117 ± 7	3	71.6 ± 5.3	3.1	58.2 ± 8.5	11.0
	TR	-	-	-	-	-	-
Mvmt 2	RG	107 ± 7	3	78.0 ± 4.3	3.1	74.4 ± 8.0	5.3
	TR	-	-	-	-	-	-
Mvmt 3	RG	110 ± 6	3	79.0 ± 4.1	3.3	72.8 ± 7.8	4.9
	TR	-	-	-	-	-	-

Table 4-3 Cup Transfer Task kinematic measures. Cup Transfer Task measures for hand distance travelled, hand trajectory variability, movement time, peak hand velocity, percent-to-peak hand velocity, number of movement units, peak grip aperture, percent-to-peak grip aperture, and percent-to-peak hand deceleration. Data are presented, for movements and segments separately, as group means and across-participant standard deviations (SD). Average within-participant variability (WPV) is also presented for each measure. Movements are: Movement 1 (Mvmt 1), Movement 2 (Mvmt 2), Movement 3 (Mvmt 3), and Movement 4 (Mvmt 4); segments are: reach-grasp (RG) and transport-release (TR).

		Hand distance travelled (mm)		**Hand trajectory variability (mm)**	**Movement time (sec)**	
		Mean ± SD	*WPV*	*Mean ± SD*	*Mean ± SD*	*WPV*
Mvmt 1	RG	380 ± 44	22	16 ± 3	0.86 ± 0.13	0.07
	TR	608 ± 36	21	16 ± 2	1.32 ± 0.15	0.10
Mvmt 2	RG	445 ± 45	30	27 ± 7	0.75 ± 0.15	0.07
	TR	635 ± 46	26	17 ± 4	1.47 ± 0.15	0.10
Mvmt 3	RG	851 ± 35	25	26 ± 6	1.10 ± 0.17	0.07
	TR	673 ± 42	28	18 ± 3	1.46 ± 0.17	0.10
Mvmt 4	RG	426 ± 43	25	24 ± 6	0.63 ± 0.09	0.06
	TR	622 ± 42	25	17 ± 3	1.36 ± 0.17	0.10

		Peak hand velocity (mm/s)		**Percent-to-peak hand velocity (%)**		**Number of movement units**	
		Mean ± SD	*WPV*	*Mean ± SD*	*WPV*	*Mean ± SD*	*WPV*
Mvmt 1	RG	818 ± 117	60	43.7 ± 7.7	6.0	1.3 ± 0.3	0.4
	TR	970 ± 79	47	21.1 ± 3.8	4.2	2.5 ± 0.4	0.8
Mvmt 2	RG	1050 ± 104	62	25.9 ± 7.7	6.7	1.3 ± 0.3	0.4
	TR	898 ± 73	46	39.9 ± 7.7	6.3	2.5 ± 0.5	0.8
Mvmt 3	RG	1435 ± 157	75	42.5 ± 5.6	6.3	1.4 ± 0.3	0.4
	TR	976 ± 53	48	25.1 ± 2.1	2.3	2.2 ± 0.7	1.0
Mvmt 4	RG	1041 ± 113	59	25.0 ± 7.2	7.5	1.3 ± 0.3	0.4
	TR	956 ± 66	47	23.8 ± 5.3	7.1	2.5 ± 0.4	0.7

		Peak grip aperture (mm)		Percent-to-peak grip aperture (%)		Percent-to-peak hand deceleration (%)	
		Mean ± SD	*WPV*	*Mean ± SD*	*WPV*	*Mean ± SD*	*WPV*
Mvmt 1	RG	99 ± 5	3	80.9 ± 5.1	4.5	69.7 ± 7.9	9.2
	TR	-	-	-	-	-	
Mvmt 2	RG	114 ± 6	3	71.9 ± 5.9	6.0	49.8 ± 8.2	8.7
	TR	-	-	-	-	-	-
Mvmt 3	RG	113 ± 7	2	81.0 ± 3.7	4.5	60.6 ± 5.7	5.4
	TR	-	-	-	-	-	-
Mvmt 4	RG	118 ± 7	3	78.1 ± 6.9	5.1	68.4 ± 13.5	10.7
	TR	-	-	-	-	-	-

Table 4-4 Pasta Bos Task statistical analysis results. Pasta Box Task results of the two-factor and one-factor repeated-measures analysis of variance (ANOVA). The results for the interaction of Movement and Segment for the two-factor repeated-measures ANOVA is reported for hand trajectory variability, movement time, peak hand velocity, and percent-to-peak hand velocity. The effect of movement for the one-way repeated measures ANOVA is reported for peak grip aperture, percent-to-peak grip aperture, and percent-to-peak-grip hand deceleration. The simple main effects ANOVA is reported for hand trajectory variability, movement time, peak hand velocity, and percent-to-peak hand velocity.
**** indicates that the F-statistic was significant at p < 0.001;**
*** indicates that the F-statistic was significant at p < 0.05;**
<< indicates that the pairwise comparison was significantly smaller at p < 0.001;
< indicates that the pairwise comparison was significantly smaller at p < 0.05.

Movement time (s)			Interaction: Mvmt x Segment F(2, 38) = 238.5**		
	Mvmt 1	Mvmt2	Mvmt 3	F (Mvmt effect)	Pairwise
Reach-grasp	0.97	0.68	0.84	(2, 38) = 255.9**	2 << 3 << 1
Transport-release	1.36	1.45	1.68	(2, 38) = 128.5**	1 << 2 << 3
Hand trajectory variability (mm)			Interaction: Mvmt x Segment F(2, 38)=22.6**		
	Mvmt 1	Mvmt 2	Mvmt 3	F (Mvmt effect)	Pairwise
Reach-grasp	17	13	19	(1.4, 27.5) = 23.6**	2 << 1,3
Transport-release	19	19	32	(1.5, 28.7) = 63.1**	1 << 3; 2 << 3
Peak hand velocity (mm/s)			Interaction: Mvmt x Segment F(2, 38) = 154.3**		
	Mvmt 1	Mvmt 2	Mvmt 3	F (Mvmt effect)	Pairwise
Reach-grasp	1008	1204	1466	(1.4, 26.4) = 183.1**	1 << 2 << 3
Transport-release	1330	1035	1470	(2, 38) = 199.1**	2 << 1 << 3
Percent-to-peak hand velocity (%)			Interaction: Mvmt x Segment F(2, 38) = 22.2**		
	Mvmt 1	Mvmt 2	Mvmt 3	F (Mvmt effect)	Pairwise
Reach-grasp	42.4	43.2	38.8	(1.4, 26.2) = 6.9*	3 < 1; 3 << 2
Transport-release	33.1	45.8	32.5	(2, 38) = 80.4**	1 << 2; 3 << 2
Peak grip aperture (mm)					
	Mvmt 1	Mvmt 2	Mvmt 3	F (Mvmt effect)	Pairwise
Reach-grasp	117	107	109	(1.3, 25.2) = 92.7**	2 << 3 << 1
Percent-to-peak grip aperture (%)					
	Mvmt 1	Mvmt 2	Mvmt 3	F (Mvmt effect)	Pairwise
Reach-grasp	71.6	77.9	79.0	(1.2, 23.5) = 61.3**	1 << 2,3; 2 < 3
Percent-to-peak hand deceleration (%)					
	Mvmt 1	Mvmt 2	Mvmt 3	F (Mvmt effect)	Pairwise
Reach-grasp	58.2	74.4	72.8	(1.1, 20.9) = 58.0**	1 << 2,3; 3 < 2

Table 4-5 Cup Transfer Task statistical analysis results. Cup Transfer Task results of the two-factor and one-factor repeated-measures analysis of variance (ANOVA). The results for the interaction of Movement and Segment for the two-factor repeated-measures ANOVA is reported for hand trajectory variability, movement time, peak hand velocity, and percent-to-peak hand velocity. The effect of movement for the one-way repeated measures ANOVA is reported for peak grip aperture, percent-to-peak grip aperture, and percent-to-peak-grip hand deceleration. The simple main effects ANOVA is reported for hand trajectory variability, movement time, peak hand velocity, and percent-to-peak hand velocity.
**** indicates that the F-statistic was significant at $p < 0.001$;**
*** indicates that the F-statistic was significant at $p < 0.05$;**
<< indicates that the pairwise comparison was significantly smaller at $p < 0.001$;
< indicates that the pairwise comparison was significantly smaller at $p < 0.05$.

Movement time (s)				Interaction: Mvmt x Segment F(3, 57) = 167.1**		
	Mvmt 1	Mvmt2	Mvmt 3	Mvmt 4	F (Mvmt effect)	Pairwise
Reach-grasp	0.86	0.75	1.10	0.63	(3, 57) = 273.2**	4 << 2 << 1 << 3
Transport-release	1.32	1.48	1.47	1.36	(2.5, 48.1) = 55.2**	1 << 2,3; 4 << 2,3
Hand trajectory variability (mm)				Interaction: Mvmt x Segment F(3, 57) = 10.2**		
	Mvmt 1	Mvmt2	Mvmt 3	Mvmt 4	F (Mvmt effect)	Pairwise
Reach-grasp	16	27	26	24	(3, 57) = 19.5**	1 << 2,3,4
Transport-release	16	17	18	17	(3, 57) = 4.42*	1 < 3
Peak hand velocity (mm/s)				Interaction: Mvmt x Segment F(3, 57) = 130.3**		
	Mvmt 1	Mvmt2	Mvmt 3	Mvmt 4	F (Mvmt effect)	Pairwise
Reach-grasp	818	1050	1435	1041	(3, 57) = 176.3**	1 << 2,3,4; 2 << 3; 4 << 3
Transport-release	970	897	976	956	(3, 57) = 18.5**	2 < 1; 2 << 3,4
Percent-to-peak hand velocity (%)				Interaction: Mvmt x Segment F(3, 57) = 132.0**		
	Mvmt 1	Mvmt2	Mvmt 3	Mvmt 4	F (Mvmt effect)	Pairwise
Reach-grasp	43.7	25.9	42.5	25.0	(3, 57) = 54.1**	2 << 1,3; 4 << 1,3
Transport-release	21.1	39.9	25.1	23.8	(1.8, 35.0) = 70.0**	1 << 2,3; 3 << 2; 4 << 2
Peak grip aperture (mm)						
	Mvmt 1	Mvmt2	Mvmt 3	Mvmt 4	F (Mvmt effect)	Pairwise
Reach-grasp	99	114	113	118	(3, 57) = 102.1**	1 << 2,3,4; 2 < 4; 3 < 4
Percent-to-peak grip aperture (%)						
	Mvmt 1	Mvmt2	Mvmt 3	Mvmt 4	F (Mvmt effect)	Pairwise
Reach-grasp	80.9	71.9	80.9	78.1	(3, 57) = 24.9**	2 << 1,3; 2 < 4
Percent-to-peak hand deceleration (%)						
	Mvmt 1	Mvmt2	Mvmt 3	Mvmt 4	F (Mvmt effect)	Pairwise
Reach-grasp	69.7	49.2	60.6	68.4	(2.1, 40.4) = 45.4**	2 << 1,3,4; 3 << 1; 3 < 4

Movement times for reach-grasp segments were significantly smaller than for transport-release segments ($p < 0.001$), even in the single case where transport distance was shorter than reach distance during Movement 3 in the Cup Transfer Task (Table 4-3). For the Pasta Box Task, post-hoc pairwise comparisons revealed that movement time for both reach-grasp and transport-release segments was significantly different between all individual movements ($p < 0.001$). For the Cup Transfer Task, post-hoc pairwise comparisons revealed that movement time for both reach-grasp and transport-release segments was significantly different between individual movements ($p < 0.001$), except for the transport-release segment of Movement 1 compared to Movement 4 ($p = 0.079$) and Movement 2 compared to Movement 3 ($p = 1.000$).

Hand trajectory graphs displaying the average hand trajectories and across-participant standard deviations are shown in Figures 4-2 and 4-3. Maximum hand trajectory variability was overall small for both tasks, ranging from 13 mm to 32 mm for the Pasta Box Task (Table 4-2) and 16 mm to 27 mm for the Cup Transfer Task (Table 4-3). For the Pasta Box Task (Table 4-4), during reach-grasp, Movement 2 was significantly less variable than Movement 1 and 3 ($p < 0.001$) and, during transport-release, Movement 3 was significantly more variable than Movement 1 and 2 ($p < 0.001$). For the Cup Transfer Task (Table 4-5), during reach-grasp, Movement 1 was significantly less variable than Movement 2, 3, and 4 ($p < 0.001$) and, during transport-release, Movement 1 was significantly less variable than Movement 3 ($p < 0.05$).

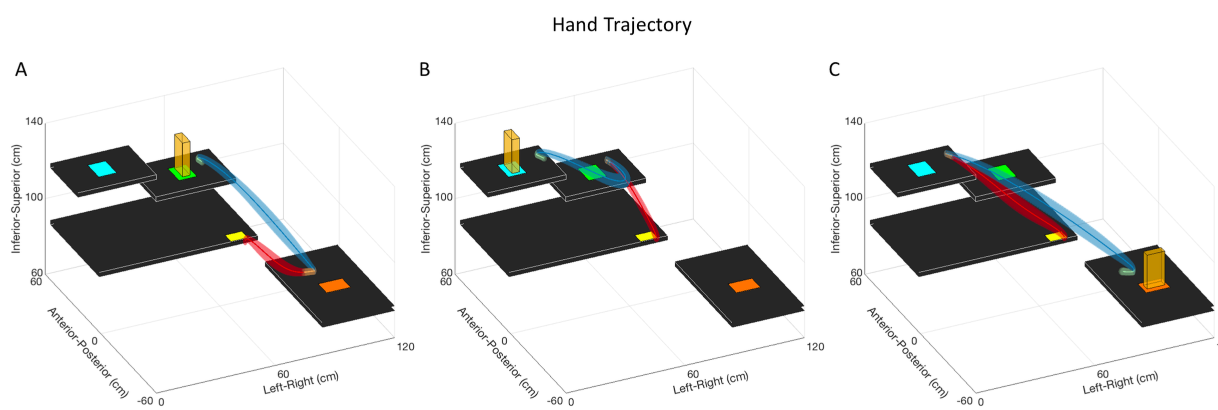

Figure 4-2 Pasta Box Task hand trajectory. Hand trajectories for the Pasta Box Task. The group average hand trajectory is plotted as a dark line, and the standard deviation of participant means as three-dimensional shading. Movement 1 (A), Movement 2 (B), and Movement 3 (C) are segmented into reach (red), grasp (orange), transport (blue), and release (green) phases. The maximum of the mean three-dimensional standard deviation was calculated for reach-grasp and transport-release segments in each movement to quantify variability, reported in Table 4-2.

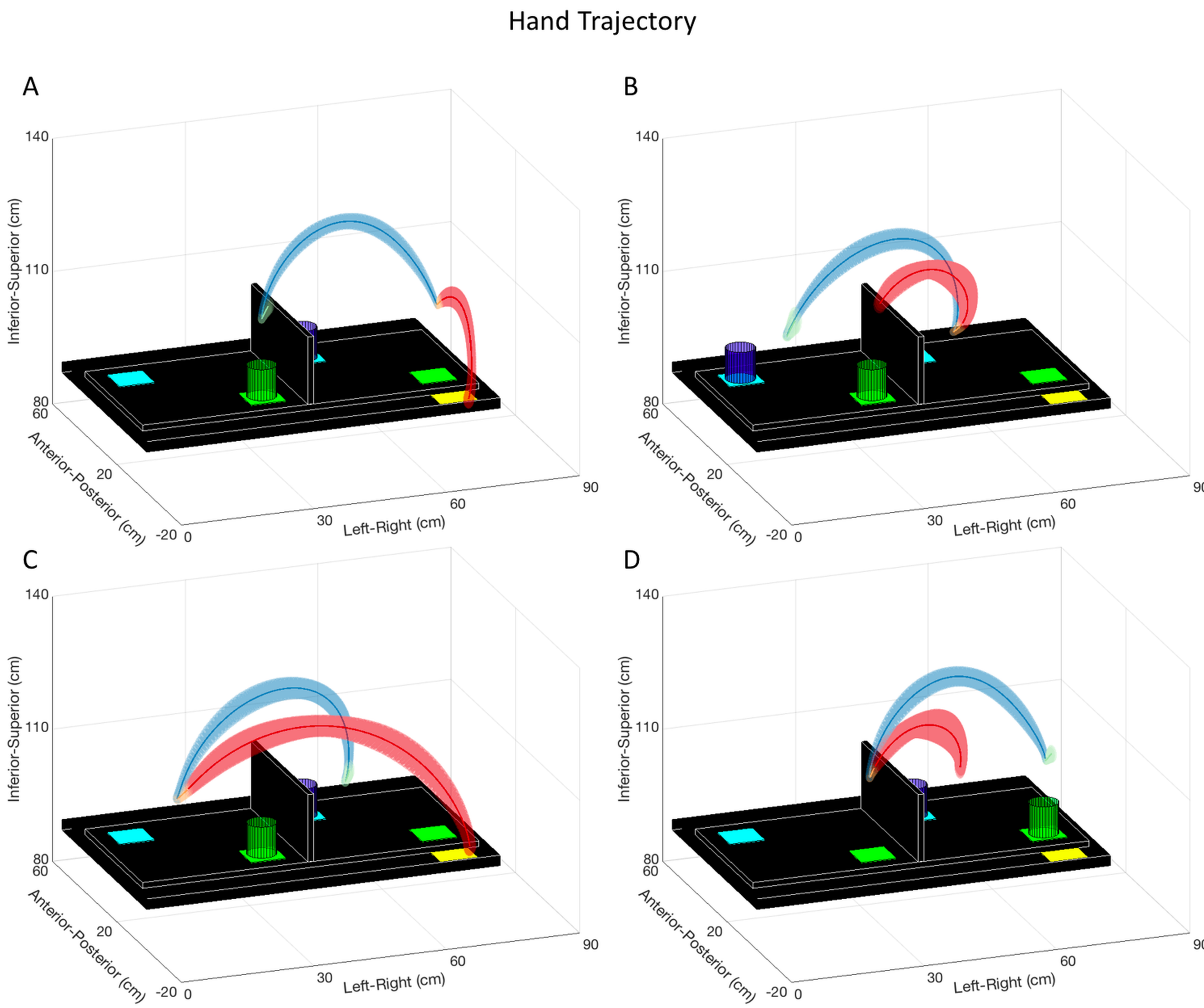

Figure 4-3 Cup Transfer Task hand trajectory. Hand trajectories for the Cup Transfer Task. The group average hand trajectory is plotted as a dark line, and the standard deviation of participant means as three-dimensional shading. Movement 1 (A), Movement 2 (B), Movement 3 (C), and Movement 4 (D) are segmented into reach (red), grasp (orange), transport (blue), and release (green) phases. The maximum of the mean three-dimensional standard deviation was calculated for reach-grasp and transport-release segments for each movement to quantify variability, reported in Table 4-3.

4.4.2 Pasta Box Task

For the Pasta Box Task (Table 4-2), movements involving the side table location affected several kinematic parameters compared to other movements. Movement 1, where participants had to turn their body and reach to the side table to pick up the box, had the lowest peak hand velocity for the reach-grasp segment (Figure 4-4A), which was significantly different from Movements 2 and 3 ($p < 0.001$). Peak grip aperture (Figure 4-5A) was also greatest for the first reach-grasp segment, which was significantly different from the reach-grasp segment of Movements 2 and 3. The peak grip aperture during the first reach-grasp segment also occurred significantly earlier than for the following two movements ($p < 0.001$) and did not align with the percent-to-peak hand deceleration. The transport-release segments of Movement 1 and 3, both involving moving the box from or to the side cart, had similar percent-to-peak hand velocities ($p = 1.000$). They were significantly lower than for Movement 2 ($p < 0.001$).

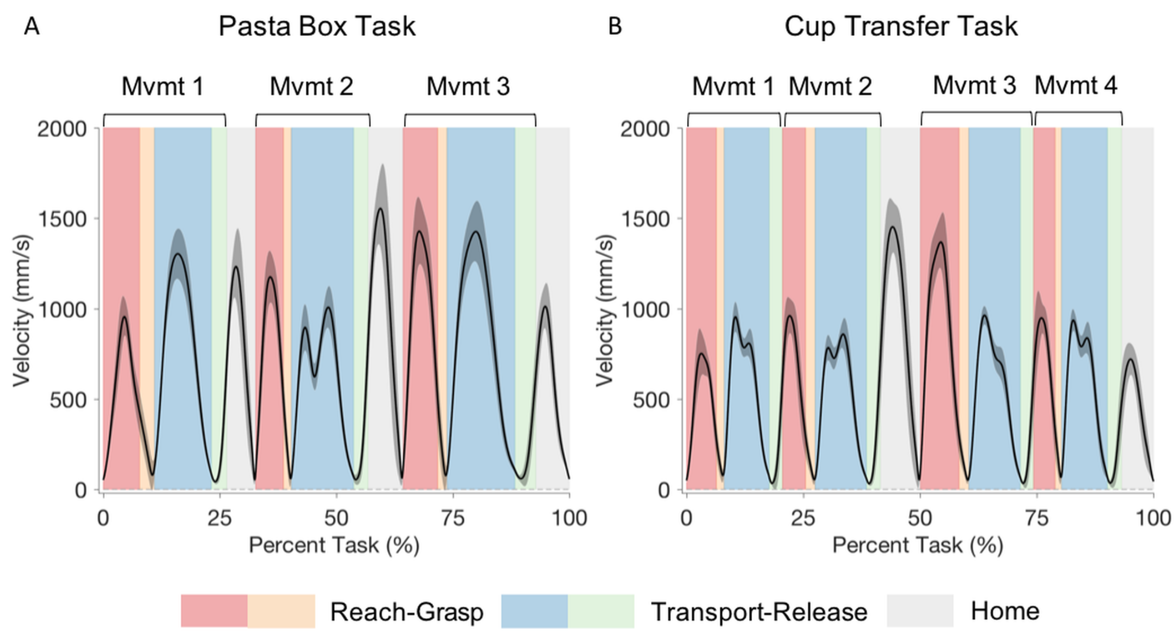

Figure 4-4 Hand velocity graphs for Pasta Box Task (A) and Cup Transfer Task (B). The solid line represents the group average, and grey shading the standard deviation of participant means. The task is segmented into reach (red), grasp (orange), transport (blue), and release (green) phases for each movement, with light grey representing the return to "home" phase. Kinematics of the reach-grasp segment and the transport-release segment were analyzed together.

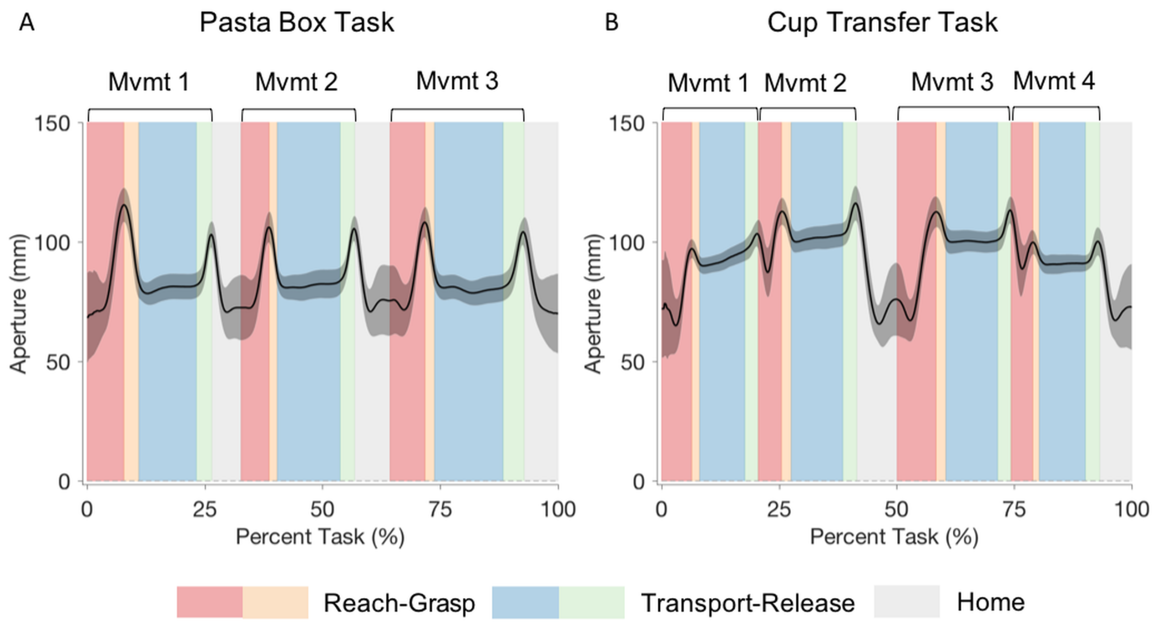

Figure 4-5 Grip aperture graphs for Pasta Box Task (A) and Cup Transfer Task (B). The solid line represents the group average, and grey shading represents the standard deviation of participant means. The task is segmented into reach (red), grasp (orange), transport (blue), and release (green) phases for each movement, with light grey representing the return to "home" phase. Kinematics of the reach-grasp segment and the transport-release segment were analyzed together.

The distinct feature of Movement 2 was that the participant had to transfer the box of pasta from the first shelf to the second shelf by moving around the middle cart barrier, which served as an obstacle. The transport-release segment of this movement had a significantly lower peak hand velocity than the other transport-release segments ($p < 0.001$), displayed two velocity peaks (indicated by the number of movement units in Table 4-2 and as seen in Figure 4-4A), and exhibited the greatest within-participant variability in percent-to-peak hand velocity.

Movement 3 had the longest distances for both reach and transport segments. Although the magnitude and timing of peak grip aperture for the reach-grasp segment was statistically different for each movement, the absolute values were very close. Reach-grasp of Movement 3 had significantly higher peak hand velocities than for reach-grasp in the other movements ($p < 0.001$), and the peak hand velocity in reach-grasp occurred significantly earlier than that of Movement 1 ($p = 0.028$) and Movement 2 ($p < 0.001$). Peak hand velocity during transport-release of Movement 3 was similarly significantly higher than that of Movement 1 and 2 ($p < 0.001$), but with a lower percent-to-peak hand velocity compared to Movement 2 ($p < 0.001$) (but not significantly different from Movement 1 ($p = 1.000$)).

4.4.3 Cup Transfer Task

Overall, peak velocities for the Cup Transfer Task (Table 4-3) were significantly higher for reach-grasp segments than transport-release segments ($p < 0.001$). Slower movement during transport was expected given the risk of spilling the compliant cups filled with beads. As evidenced by the hand velocity graph (Figure 4-4B) and the number of movement units (Table 4-3), all transport-release segments displayed small, double hand velocity peaks, reflecting a consequence of transporting the cup over an obstacle in the vertical plane.

The Cup Transfer Task was unique in that it required two different grasp patterns, which we hypothesized would affect grip aperture and velocity of movements based on confidence in modulating grip patterns to not crush the cup and spill the contents. Movement 1 had the shortest distance to reach and the lowest peak velocity (Figure 4-4B) compared to all the other segments ($p < 0.001$). Movement 1 also had the lowest peak grip aperture (Figure 4-5B) compared to the other three movements ($p < 0.001$). The transport velocity for Movement 1 was similar to that of Movements 3 and 4 ($p = 1.000$).

Movement 2 required a change in grasp to a side grasp of the cup, and displayed a similar peak grip aperture to Movement 3 also requiring a side grasp ($p = 0.959$), but was significantly different from the top grasps ($p < 0.05$). Although Movements 2 and 3 had similar grip apertures, there were differences in the velocity profiles. Movement 2 had a lower and earlier peak hand velocity than Movement 3, and the earliest deceleration peak of all the reach-grasp segments. This slowed movement was also seen in the transport-release segment of Movement 2, which had the lowest peak hand velocity of all the transport-release segments. The percent-to-peak grip aperture occurred significantly earlier in the reach-grasp segment of Movement 2 compared to the other 3 movements ($p < 0.01$).

In contrast, the reach-grasp segment in Movement 3 had the highest peak hand velocity. The hand velocity for the transport-release segment of Movement 3 was not significantly different from

Movement 1 ($p = 1.000$) and 4 ($p = 0.137$). Movement 4 had the largest peak grip aperture ($p < 0.05$). It otherwise showed similar characteristics in percent-to-peak grip aperture and percent-to-peak hand deceleration as Movement 1, which had the same grasp.

4.4.4 Between-Session Repeatability

Both the Pasta Box Task and Cup Transfer Task presented mostly good repeatability (ICC > 0.75) for movement time, peak hand velocity, percent-to-peak hand velocity, peak grip aperture, percent-to-peak grip aperture, and percent-to-peak hand deceleration.

For the Pasta Box Task (Table 4-6), poor to moderate repeatability (ICC values of below 0.75) was found for only two measures: peak hand velocity and percent-to-peak hand velocity for the transport-release segment of Movement 1. For the Cup Transfer Task (Table 4-7), poor to moderate repeatability (ICC values of below 0.75) was found for six of the 36 measures: peak hand velocity for the transport-release segment of Movement 1, Movement 3, and Movement 4, as well as for percent-to-peak hand velocity, percent-to-peak grip aperture, and percent-to-peak hand deceleration for the reach-grasp segment of Movement 1.

For the Pasta Box Task (Table 4-6), SEM values ranged from 1 to 7% of the average absolute measurement value across measures, and MDC ranged from 3 to 20% across measures. For the Cup Transfer Task (Table 4-7), SEM values ranged from 1 to 15% across measures and MDC ranged from 2 to 42% across measures.

Table 4-6 Pasta Box Task repeatability results. Repeatability analysis was performed for movements and segments separately, on movement time, peak hand velocity, percent-to-peak hand velocity, peak grip aperture, percent-to-peak grip aperture, and percent-to-peak hand deceleration. Repeatability measures include intra-class correlation (ICC) with corresponding 95% confidence intervals, standard error of measurement (SEM), and minimal detectable change (MDC). ICC values above 0.90 are presented in bold. ICC values below 0.75 are presented in italics. ICC values that failed the F-test ($p > 0.05$) are presented with an asterisks (*), indicating the validity of the ICC may be compromised for this result. Movements are: Movement 1 (Mvmt 1), Movement 2 (Mvmt 2), and Movement 3 (Mvmt 3); segments are: reach-grasp (RG) and transport-release (TR).

		Movement time (sec)			**Peak hand velocity (mm/s)**			**Percent-to-peak hand velocity (%)**		
		ICC	*SEM*	*MDC*	*ICC*	*SEM*	*MDC*	*ICC*	*SEM*	*MDC*
Mvmt 1	RG	0.84 (0.37-0.96)	0.035	0.098	0.89 (0.54-0.97)	38	106	0.90 (0.61-0.98)	1.4	3.8
	TR	0.81 (0.25-0.95)	0.046	0.128	*0.56 (-0.77-0.89)**	56	156	*0.74 (-0.06-0.93)*	2.4	6.6
Mvmt 2	RG	0.88 (0.50-0.97)	0.030	0.083	0.79 (0.15-0.95)	64	177	**0.95 (0.79-0.99)**	1.6	4.4
	TR	0.86 (0.45-0.97)	0.057	0.159	**0.91 (0.64-0.98)**	30	84	0.83 (0.30-0.96)	2.0	5.5
Mvmt 3	RG	**0.93 (0.70-0.98)**	0.029	0.081	**0.93 (0.72-0.98)**	47	130	0.89 (0.57-0.97)	2.1	5.7
	TR	0.89 (0.56-0.97)	0.052	0.145	0.78 (0.10-0.94)	40	112	0.86 (0.45-0.97)	1.6	4.4
		Peak grip aperture (mm)			**Percent-to-peak grip aperture (%)**			**Percent-to-peak hand deceleration (%)**		
		ICC	*SEM*	*MDC*	*ICC*	*SEM*	*MDC*	*ICC*	*SEM*	*MDC*
Mvmt 1	RG	**0.95 (0.78-0.99)**	2	4	0.88 (0.50-0.97)	1.8	4.9	0.84 (0.35-0.96)	3.4	9.5
Mvmt 2	RG	**0.92 (0.68-0.98)**	2	4	**0.95 (0.81-0.99)**	1.0	2.7	0.80 (0.20-0.95)	2.6	7.2
Mvmt 3	RG	**0.95 (0.79-0.99)**	1	4	0.87 (0.47-0.97)	1.3	3.7	0.75 (0.01-0.94)	2.4	6.6

Table 4-7 Cup Transfer Task repeatability results. Repeatability analysis was performed, for movements and segments separately, on movement time, peak hand velocity, percent-to-peak hand velocity, peak grip aperture, percent-to-peak grip aperture, and percent-to-peak hand deceleration. Repeatability measures include intra-class correlation (ICC) with corresponding 95% confidence intervals, standard error of measurement (SEM), and minimal detectable change (MDC). ICC values above 0.90 are presented in bold. ICC values below 0.75 are presented in italics. ICC values that failed the F-test ($p > 0.05$) are presented with an asterisks (*), indicating the validity of the ICC may be compromised for this result. Movements are: Movement 1 (Mvmt 1), Movement 2 (Mvmt 2), Movement 3 (Mvmt 3), and Movement 4 (Mvmt 4); segments are: reach-grasp (RG) and transport-release (TR).

		Movement time (sec)			**Peak hand velocity (mm/s)**			**Percent-to-peak hand velocity (%)**		
		ICC	*SEM*	*MDC*	*ICC*	*SEM*	*MDC*	*ICC*	*SEM*	*MDC*
Mvmt 1	RG	0.83 (0.33-0.96)	0.032	0.089	0.77 (0.07-0.94)	64	176	*0.54 (-0.84-0.89)**	4.6	12.6
	TR	0.85 (0.41-0.96)	0.042	0.116	*0.65 (-0.43-0.91)**	50	139	0.82 (0.25-0.95)	0.9	2.5
Mvmt 2	RG	0.85 (0.40-0.96)	0.033	0.092	**0.96 (0.83-0.99)**	26	72	**0.93 (0.71-0.98)**	2.1	5.9
	TR	0.81 (0.22-0.95)	0.053	0.147	0.76 (0.03-0.94)	29	81	**0.91 (0.63-0.98)**	2.8	7.8
Mvmt 3	RG	0.85 (0.41-0.96)	0.045	0.125	0.76 (0.05-0.94)	60	166	**0.91 (0.62-0.98)**	2.1	5.9
	TR	0.76 (0.05-0.94)	0.068	0.189	*0.52 (-0.93-0.88)**	25	68	0.85 (0.38-0.96)	0.8	2.1
Mvmt 4	RG	0.75 (0.01-0.94)	0.031	0.086	0.84 (0.35-0.96)	50	139	0.78 (0.10-0.95)	3.8	10.5
	TR	0.85 (0.38-0.96)	0.058	0.162	*0.64 (-0.44-0.91)**	29	80	**0.99 (0.96-1.00)**	**0.7**	2.0

		Peak grip aperture (mm)			**Percent-to-peak grip aperture (%)**			**Percent-to-peak hand deceleration (%)**		
		ICC	*SEM*	*MDC*	*ICC*	*SEM*	*MDC*	*ICC*	*SEM*	*MDC*
Mvmt 1	RG	**0.97 (0.87-0.99)**	1	3	*0.60 (-0.61-0.90)**	1.8	5.0	*0.68 (-0.30-0.92)**	4.1	11.4
Mvmt 2	RG	**0.97 (0.86-0.99)**	1	3	0.79 (0.14-0.95)	2.1	5.9	0.86 (0.43-0.97)	2.8	7.9
Mvmt 3	RG	**0.97 (0.86-0.99)**	1	2	0.81 (0.24-0.95)	1.6	4.3	**0.95 (0.78-0.99)**	1.5	4.3
Mvmt 4	RG	**0.96 (0.83-0.99)**	2	4	0.86 (0.45-0.97)	2.2	6.0	0.84 (0.36-0.96)	5.2	14.5

4.5 Discussion

The purpose of developing new standardized functional tasks representative of real-world ADLs was to create a meaningful assessment metric for clinical populations with upper limb impairments, that specifically focused on quantifying hand kinematics. Reach-grasp tasks have been shown to provide insights into altered motor control strategies in populations with impaired upper limb function (Alt Murphy et al., 2011; Butler et al., 2010; Lang et al., 2005; Major et al., 2014; van Vliet and Sheridan, 2007; Zackowski et al., 2002). The importance of involving objects in goal-directed tasks with a functional context has been previously demonstrated as resulting in smoother, faster, more preplanned movement compared to non-goal directed movement through space (Wu et al., 1998a). Using natural objects for completing a task and providing functional information on the objects, rather than simulated devices, is important to enhance functional performance in both normative and impaired populations (Wu et al., 1998b). Our tasks, designed to be consistent with these parameters and also the requirements of known clinical upper limb assessments (Hudak et al., 1996; Jebsen et al., 1969; Light et al., 2002; Lindner et al., 2009; Lyle, 1981; Mathiowetz et al., 1985; Resnik et al., 2013a), were relatively easy for non-disabled individuals to perform. However, since errors were made by participants, the tasks required some level of attention and concentration. This may be valuable for assessing clinical populations with not only motor difficulties but also motor planning impairments.

The tasks had specific movement sequences that were standardized, repeatable, of short duration, and consistently performed by individual participants. Other tasks used in literature have shown low within-participant variability (Butler et al., 2010; Jaspers et al., 2011b; Vanezis et al., 2015), however typically using more constrained tasks not as representative of real-world object interactions. Within-participant variability is an important factor to assess as, for some clinical populations, increased variability in motor performance is a key indicator of poor motor skill, and may indicate the adoption of various strategies for accomplishing a task rather than converging on one strategy. For example, prosthesis users have been shown to have increased variability in upper limb angular kinematics, as reflected by increased average standard deviation (Major et al., 2014), whereas more skilled prosthesis users have less deviation in end-point kinematic profiles from non-disabled movement patterns (Bouwsema et al., 2012). The measurement of variability may play an important role given that it has been shown in the occupational literature that both kinematic compensation and motor variability are associated with musculoskeletal pain (Madeleine, 2010). The inclusion of mean participant standard deviation as a measure of within-participant variability in this normative data set will allow comparison in future study of impaired populations. The between-session repeatability of the task was also found to be good for 55 out of 63 parameters, which is a prerequisite prior to investigating sensitivity to change in clinical populations.

The task design with specific sequencing allowed for segmentation of movements into the crucial phases of reaching and grasping, and transporting and releasing objects within the same task. This allows examination of discrete characteristics of hand movement pertaining to hand trajectory, hand velocity, and grip aperture for each of these phases. This is important as many clinical populations will have impaired dexterity impacting grasp, which has been extensively investigated (Alt Murphy et al., 2011, 2006); however, valuable information can also be obtained by examining control of the hand during transport, such as grip modulation. In addition, grasp features are known to be affected by the task goal and setting (Valyear et al., 2011); therefore, it is most ecologically valid to use tasks that not only reach and grasp but involve a logical next step of movement and placement of the object.

The influence of an object's intrinsic and extrinsic parameters on hand kinematics was consistent with prior literature**.** Location of the object influenced several parameters, particularly the first movement of the Pasta Box Task where the box of pasta was not within the direct field of view and required a turn of the body and the head for the grasp. This misalignment of the body space to the visual space has been shown to increase the latency of the movement towards a target and decrease accuracy (Fisk and Goodale, 1985; Prablanc et al., 1979). This first movement also required the arm to move multiple DoFs across several planes (i.e., sagittal, transverse, and coronal planes) to complete the movement accurately. Therefore, a greater deceleration phase was necessary, evidenced by the hand velocity peaks occurring earlier than for other movements. This aligns with previous research by Fisk & Goodale who found hand velocity peaks to occur roughly around one third of the movement for lateral reaches (Fisk and Goodale, 1985), compared to studies that restricted reaching tasks to single plane movement and reported more symmetrical hand velocity profiles (Morasso, 1981).

The location of the cups in the task space and the required grasp conformation also influenced reaching strategies. The first reach-grasp of the Cup Transfer Task showed the smallest grip aperture, suggesting confidence with the upcoming grasp of the top of the cup, but a slowed velocity of the reach likely due to the short distance. The two cylindrical side grasps showed similar grip apertures, but were different in movement strategies in that the first cylindrical side grasp showed several features suggesting it was the reach with the highest perceived risk, with lower, earlier peak velocity and the earliest deceleration. This is consistent with previous studies where hand velocity was lower during the reach when the task following the approach required precision (Claxton et al., 2003; Marteniuk et al., 1987). Three of the transport release segments showed peak velocities occurring no later than 25% of the movement, indicating that movement of the compliant cup with risk of spillage was potentially challenging. This is consistent with Butler et al. who found lower percent-to-peak hand velocity values for the segment of their task where the performer had to bring a cup to their mouth, suggesting that this movement was riskier and required more conservative control strategies (Butler et al., 2010).

Both tasks involved obstacle avoidance; in the vertical plane for every movement of the cups, and in the horizontal plane for the second movement of the box of pasta. As previously shown by Chapman & Goodale, obstacles change the spatiotemporal characteristics of hand movement by increasing movement time and decreasing peak hand velocity (Chapman and Goodale, 2008). This effect is even greater when obstacles are closer to the performer and on the side of the reaching arm (Chapman and Goodale, 2008). These differences in spatiotemporal characteristics may have been amplified in our task since these trends were observed during the transport-release segment as opposed to the reach-grasp segment, where moving the object adds a further level of uncertainty.

The challenges presented by these varied intrinsic and extrinsic properties is expected to result in significant performance differences in conditions with impaired hand sensation and impaired upper limb function. Reaching and grasping are functionally linked to the specific task, with the characteristics of the object determining the relative timing of peak grip aperture and peak hand deceleration (Marteniuk et al., 1990). Abnormalities in these features resulting in decoupling of reach and grasp have been shown in prosthesis users (Bouwsema et al., 2010), cerebellar lesions (Zackowski et al., 2002), spinal cord injury (Mateo et al., 2015) and in stroke populations (Nowak, 2008), suggesting that this type of kinematic analysis could have applicability to multiple populations with upper limb impairment.

4.5.1 Limitations and Future Work

The assessment of normative hand movement characteristics demonstrated consistent trends across varying task challenges. The limitations of the current study include the assessment of only between-session repeatability, not the repeatability among different test administrators and study sites. Further study of inter-rater repeatability will assist with determining reproducibility of the task assessment. Considering that the presented normative data set establishes an ideal young adult performance standard, further work may focus on establishing differences between the sexes or with aging cohorts to obtain a fully comparative data set for populations with impairment. Finally, future work will also test the application of this methodology in populations with upper limb impairments, and validate the measures against other clinically validated hand outcome assessments in these populations.

4.6 Conclusion

Standardized upper limb functional tasks which mimic ADLs and incorporate elements of risk and accuracy, lateral reaches, reaches crossing the body's midline, objects of different shapes and sizes, and different grasp patterns to assess hand movements were developed. A normative dataset for hand movement was created based on non-disabled performance characterizing hand trajectory, hand velocity, and grip aperture features for reach-grasp and transport-release segments of the movements. These features verified that the tasks challenged a variety of motor control strategies, and these unique movement characteristics were reflected in the quantitative results while being highly consistent within-performers. In addition to the low within-participant and between-participant variability for these complex tasks, a repeatability analysis showed that this novel assessment approach has good between-session repeatability. This assessment promises to be a valuable tool for future research in populations with upper limb impairments.

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Chapter 5. Characterization of normative angular joint kinematics during two functional upper limb tasks

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The content of this chapter is identical to the material presented in the publication, except for the text formatting which was done according to University of Alberta requirements. Parts of this work have also been presented at scientific conferences including *The 40th Annual Meeting of the American Society of Biomechanics,* held on August 2 to August 5, 2016, in Raleigh, North Carolina, United States, and *The Spotlight on Research Breakfast*, held on October 20, 2016, in Edmonton, Canada.

5.1 Abstract

Background: Optical motion capture is a powerful tool for assessing upper body kinematics, including compensatory movements, in different populations. However, the lack of a standardized protocol with clear functional relevance hinders its clinical acceptance.

Research Question: The objective of this study was to use motion capture to: (1) characterize angular joint kinematics in a normative population performing two complex, yet standardized upper limb tasks with clear functional relevance; and (2) assess the protocol's intra-rater reliability.

Methods: Twenty non-disabled adults performed the previously developed Pasta Box Task and Cup Transfer Task. The kinematics of the upper body were captured using an optoelectronic motion capture system and rigid plates with reflective markers. Angular joint trajectories, peak angle, RoM, and peak angular velocity were extracted for the trunk, shoulder, elbow, forearm, and wrist. ICC was used to assess the intra-rater reliability of the kinematic measures.

Results: Both tasks required minimal trunk motion. Cross-body movements required greater RoM at the trunk, shoulder, and elbow joints compared to movements in front of the body. Reaches to

objects further away from the body required greater trunk and elbow joint RoM compared to reaches to objects closer to the body. Transporting the box of pasta required the wrist to maintain an extended position. The two different grasp patterns in the Cup Transfer Task forced the wrist into a flexed and ulnar-deviated position for the near cup, and an extended and radial-deviated position for the far cup. For both tasks, the majority of measures displayed ICC values above 0.75, indicating good reliability.

Significance: Our protocol and functional tasks elicit a degree of movement sensitivity that is not available in current clinical assessments. Our study also provides a comprehensive dataset that can serve as a normative benchmark for quantifying movement compensations following impairment.

5.2 Introduction

Sensorimotor dysfunction of the upper limb is common for a wide variety of disorders, ranging from stroke (Lang et al., 2005) to amputation (Metzger et al., 2012). Impairments in arm function disrupt normal reach and grasp, altering typical movement patterns at the elbow, shoulder, and trunk (Klein et al., 2011). These motor compensations (Gates et al., 2016; Levin et al., 2008) can be maladaptive and result in musculoskeletal pain or overuse injuries (Levin et al., 2008). Current best practice for preventing overuse injuries includes early symptom detection and treatment, retraining proper movement patterns, and lifestyle changes (Gambrell, 2008). However, to prescribe and evaluate restorative interventions, it is critical to be able to accurately assess limb use patterns and to characterize underlying motor strategies.

Several upper limb performance tests exist that are designed to assess global upper limb function (Resnik et al., 2013a; Velstra et al., 2011); however, they do not quantify specific changes in joint movement (Alt Murphy et al., 2006). An effective method of quantifying upper limb movement is to use motion capture for tracking upper body segments (Winter, 2009). Analysis of the 3D angular kinematics provides insight into limb use patterns and underlying motor control strategies. Specifically, RoM has shown to indicate active joint range, motor control, muscle power, and an individual's ability to complete a task (Aizawa et al., 2013). RoM has been used in non-disabled individuals (Valevicius et al., 2018b) and those with impairments (Alt Murphy et al., 2011) to quantify proximal joint adaptations required to successfully complete a task (Gates et al., 2016), and to identify altered movement strategies with different interventions (Hebert et al., 2014). In addition to RoM, other clinically meaningful outputs of 3D kinematic analysis include joint angle profiles (Alt Murphy et al., 2006; Gates et al., 2016; Hebert et al., 2014), peak joint angle needed for task completion (Petuskey et al., 2007), and peak angular velocity (Alt Murphy et al., 2011). Joint angle profiles allow to visualize limb movement patterns. Given that upper limb movement is not cyclical, many different joint movement strategies can be selected to successfully complete a task, which is reflected in joint angle profiles (Gates et al., 2016). Peak joint angle is indicative of the extreme of joint movement required for a given task. This measure also allows to see the direction of compensation among individuals with impairments (Alt Murphy et al., 2011; Petuskey et al., 2007). Finally, peak angular velocity is a valuable measure to investigate muscle torque production (Chang et al., 2005) and has been found to be the best measure to discriminate between non-disabled individuals and those who have suffered a stroke (Alt Murphy et al., 2011). Integrating these kinematic measures into the assessment of populations with upper limb impairments can allow accurate quantification of movement compensations during specific tasks.

Due to the complexity of upper body movement and the ability to complete a task using variable strategies, comparison across studies is, however, difficult (Engdahl and Gates, 2018). Most studies employ different kinematic protocols, including a variety of movement tasks and marker sets (Kontaxis et al., 2009; Valevicius et al., 2018b), and lack distinct, clinically based assessment routines (Alt Murphy et al., 2006). The development of reliable kinematic protocols for assessing goal-oriented functional movements is important for clinical practice (Alt Murphy et al., 2006) – as such protocols can lead to a wider use of motion capture in clinical environments. Protocols must also exhibit consistency and reliability (Alt Murphy et al., 2006; Engdahl and Gates, 2018), and establish a normative dataset in controls (Alt Murphy et al., 2006).

In the interest of developing a reliable, ecologically valid upper limb kinematic assessment with clinical relevance, we have previously developed a task protocol using optoelectronic motion capture and a simple-to-use cluster marker set (Boser et al., 2018) for two standardized functional tasks (Valevicius et al., 2018a). The tasks incorporate complex movements, fulfilling clinicians' goals to simulate real-world environments. Secondly, the functional task movements, while complex, are highly standardized and constrained, allowing segmentation into simple movement phases for meaningful 3D kinematic analysis. Thirdly, our tasks elicit multidimensional movements of the entire upper limb kinematic chain, such as cross-body movements, reaching to different heights, and arm rotations, to challenge various upper limb impairments. A previous study by Valevicius et al. used this novel protocol to demonstrate the reliability of hand kinematics in non-disabled individuals, including hand trajectory, hand velocity, and grip aperture (Valevicius et al., 2018a). However, this protocol has not yet been applied to fully characterize the movement of the upper body's kinematic chain.

In this light, the purpose of the present study was to: (1) characterize normative angular kinematics, namely angular joint trajectories, peak joint angle, RoM, and peak angular velocity, for the two standardized functional tasks that fulfill the abovementioned requirements (Valevicius et al., 2018a); and (2) assess the intra-rater reliability for peak angle, RoM, and peak angular velocity. Developing a consistent and repeatable test protocol for motion capture of angular kinematics will allow its future application to a variety of upper limb sensorimotor impairments relative to an established normative dataset.

5.3 Methods

5.3.1 Study Participants

Twenty non-disabled individuals (9 females and 11 males; 18 right-handed and 2 left-handed; age 25.8±7.2 years; height 173.8±8.3 cm) participated in the study. Participants had no upper body pathology or history of neurological or musculoskeletal injury in the past two years. They provided written informed consent to the experimental procedures, which were 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).

5.3.2 Experimental Setup and Procedures

3D marker trajectories were collected at 120 Hz using a 12-camera Vicon Bonita motion capture system (Vicon Motion Systems Ltd, Oxford, UK). A *Clusters Only* kinematic model previously described in Boser et al. was used in the present study (Boser et al., 2018). Rigid plates with three or four 11 mm reflective markers were attached to the following upper body segments using hypo-allergenic, double-sided tape: pelvis, trunk, upper arms, forearms (with four markers on each plate), and hands (with three markers on each plate) (Figure 5-1 & Table 5-1). A specific calibration pose was recorded prior to data collection. This calibration pose was required to align the axes of rotation of the upper body segments with the global coordinate system. The participant was asked to stand in a modified anatomical pose where the shoulder was at zero degrees of abduction, and the axes passing through the epicondyles and radial and ulnar styloids where aligned with the frontal plane (Boser et al., 2018).

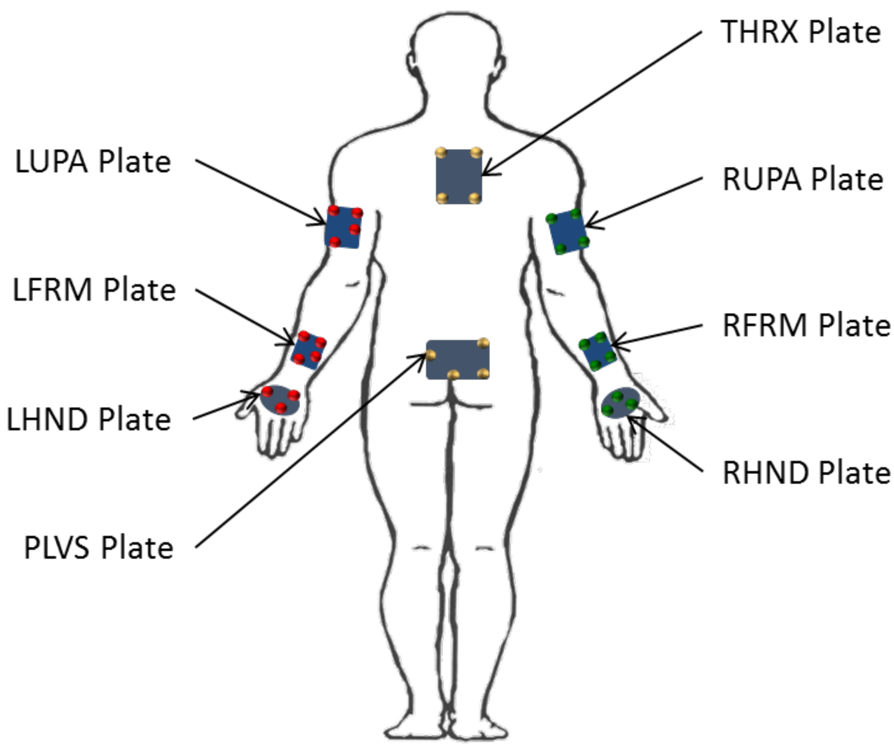

Figure 5-1 Location of marker cluster plates, relative to the upper body, and of the markers, relative to the cluster plates. Plates were attached to the pelvis (PLVS), trunk (THRX), left and right upper arm (LUPA & RUPA), left and right forearm (LFRM & RFRM), and left and right hand (LHND & RHND). All plates had four markers each, except for the hand plates, which had three markers each.

Table 5-1 Location of marker cluster plates, relative to the upper body, and of the markers, relative to the cluster plates. Plates were attached to the pelvis (PLVS), trunk (THRX), left and right upper arm (LUPA & RUPA), left and right forearm (LFRM & RFRM), and left and right hand (LHND & RHND). All plates had four markers each, except for the hand plates, which had three markers each.

Segment	Abbreviation	Number of Markers	Location Description
Pelvis	PLVS	4	Posterior pelvis, below PSIS
Thorax	THRX	4	Posterior thorax, between T10 and C7
Upper Arm (bilateral)	UPA	4	Middle of upper arm, lateral surface
Forearm (bilateral)	FRM	4	Dorsal surface of forearm, just above styloid processes
Hand (bilateral)	HND	3	Center of dorsal surface of hand

Two standardized functional upper limb tasks, the Pasta Box Task and Cup Transfer Task (Figure 4-1), were used in this protocol (Valevicius et al., 2018a). For the Pasta Box Task, participants had to reach for a box of pasta positioned on the right-hand side of their body, pick it up and move it to a shelf directly in front of them (*Movement 1*). They then had to return their hand to the initial 'Home' (start) position, reach for the box of pasta again, pick it up, and move it to a higher shelf on the left-hand side of their body (*Movement 2*), thereby crossing the body's midline. Finally, they had to return their hand to 'Home', reach for the box of pasta again, pick it up, and move it to its initial location on the right-hand side of their body (*Movement 3*). For the Cup Transfer Task, participants had to pick up the first cup positioned in the near area of the box on the right side and move it over a partition to a target location on the left side of the box, grasping the top of the cup (*Movement 1*). Next, they had to pick up a second cup from its initial location in the far area of the right side of the box and move it over the partition to a target location on the left side of the box, using a side grasp (*Movement 2*). Participants then had to return their hand to the initial 'Home' position and repeat the sequence in reverse, moving the far cup on the left side back over to the right-side starting position (*Movement 3*), and then the near cup from the left side back over to the starting position on the right (*Movement 4*). The cups were compliant (Dixie® Consumer Products LLC, Atlanta, USA) and filled with therapeutic beads to add an element of risk (spillage) and to require grasp force modulation. For both tasks, the 'Home' position was standardized by attaching it along the near edge of the table top, exactly 12.5” to the right of the table top’s center line. Participants started both tasks with their hand at rest on the ‘Home’ position. Throughout the task, they were simply required to touch the ‘Home’ position with their hand between ‘Movements’ and not necessarily come to a complete rest. Task order was block-randomized, with ten participants starting with the Pasta Box Task and ten with the Cup Transfer Task. If an error occurred during a trial, the error type was recorded, and that trial marked as unsuccessful. Each participant completed the tasks until 20 successful attempts were recorded. Ten participants (5 females and 5 males; 9 right-handed and 1 left-handed; age 26.4±6.9 years; height 173±9 cm) returned for a second testing session several months (7.5 months±11 days) after the initial testing, to assess the intra-rater reliability of the obtained kinematic measures. Repeat sessions were administered by the same assessor as for the initial session.

5.3.3 Experimental Data Anlysis

Marker data were filtered using a 2nd order, low-pass Butterworth filter with a cutoff frequency of 6 Hz (Winter, 2009). Filtered marker data were used to calculate 3D angular joint kinematics. Global and local coordinate systems, Cardan angle rotation sequence, and joint angle computations were implemented following the procedures in Boser et al. (Boser et al., 2018). Ten DoFs were included in the analysis: 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 overall, average joint angle trajectories with between-participant SD bands were plotted for each DoF studied. Peak joint angle, RoM, and peak angular velocity values were extracted from joint angle time series of individual trials.

Using hand velocity, object velocity, and grip aperture, trial data were segmented into reach, grasp, transport, and release phases and time-normalized following the procedures in Valevicius et al. (Valevicius et al., 2018a). Each phase was illustrated in a different color in the figures, to enhance visual interpretation. For the purpose of 3D kinematic analysis, data were analyzed by ‘Movement’, consisting of a set of reach, grasp, transport, and release phases. The ‘Return to Home’ motion after specific movements was not considered a phase within a ‘Movement’ and was therefore not included in the analysis; however, this motion was still included in the graphical presentation of the angular kinematics using a different color. The Pasta Box Task and Cup Transfer Task were comprised of 3 and 4 movements, respectively.

5.3.4 Statistical Analysis

Statistical analysis was completed using the SPSS software (IBM Corporation, Armonk, NY, USA). Intra-rater reliability was assessed by calculating the ICC for model (2,k), the SEM, and the MDC (Weir, 2005) between the first and second session of the ten returning participants. SEM was calculated as the square root of the mean square error term from the analysis of variance (Weir, 2005). MDC was calculated using the equation $MDC = SEM \cdot 1.96 \cdot \sqrt{2}$, where 1.96 is the z-score associated with the 95% confidence interval (Weir, 2005). ICC, SEM, and MDC values were obtained for peak joint angle, RoM, and peak angular velocity. ICC values above 0.90 were considered to show reasonable agreement for clinical measurements, above 0.75 good reliability, and below 0.75 poor to moderate reliability (Portney and Watkins, 2009). F-Tests ($p < 0.05$) were performed to check for the validity of the ICC values.

5.4 Results

5.4.1 Pasta Box Task

Angular joint trajectories for the Pasta Box Task are shown in Figure 5-2. The mean peak angle, RoM, and peak angular velocity, along with their between-participant SD and within-participant variability, are listed for each movement of the Pasta Box Task in Table 5-2. There was very little trunk flexion/extension across all movements, with only 4±1 to 5±2 degrees of RoM. The trunk distinctly bended and rotated to the right during Movement 1 reach and Movement 3 transport (to the side table), whereas, during Movement 2 transport and Movement 3 reach (across the body), the trunk distinctly bended and rotated to the left (Figure 5-2). All three movements started with the shoulder in a near neutral position, reaching peak flexion when grasping (67±11 degrees) or releasing (65±12 degrees) the box on the raised shelves in front of the participant. The same was observed for peak shoulder internal rotation values (34±11 degrees), particularly for movements to the second shelf requiring a cross-body reach. The shoulder maintained a mostly abducted position throughout the task, with peak shoulder abduction occurring during Movement 1 reach (–25±7 degrees) when picking up the box of pasta from the side table. Greater than 90 degrees of peak elbow flexion was required to transport the box of pasta (Figure 5-2). When grasping or releasing the box, the elbow was closer to full extension (minimum flexion angle: 15±8 degrees). Each movement started with the forearm in a pronated position and progressively supinated throughout the reach. Movement 3 required the greatest range of pronation/supination (90±16 degrees). The wrist was in extension for the entirety of the task, with the least amount of wrist extension displayed during Movement 2 transport (–11±14 degrees). Reaching for the box on the cart shelves required wrist ulnar deviation (peak angle: 19±8 degrees) and placing the box back on the side table required wrist radial deviation (peak angle: –12±7 degrees). Trunk DoFs displayed the lowest angular velocities (14±4 to 60±11 degrees/sec). For shoulder, elbow, and wrist joints, flexion/extension movement displayed the largest peak angular velocities, indicating faster angular changes in the sagittal plane of motion. Overall, largest angular velocity values (above 250 degrees/sec) were observed for elbow flexion/extension.

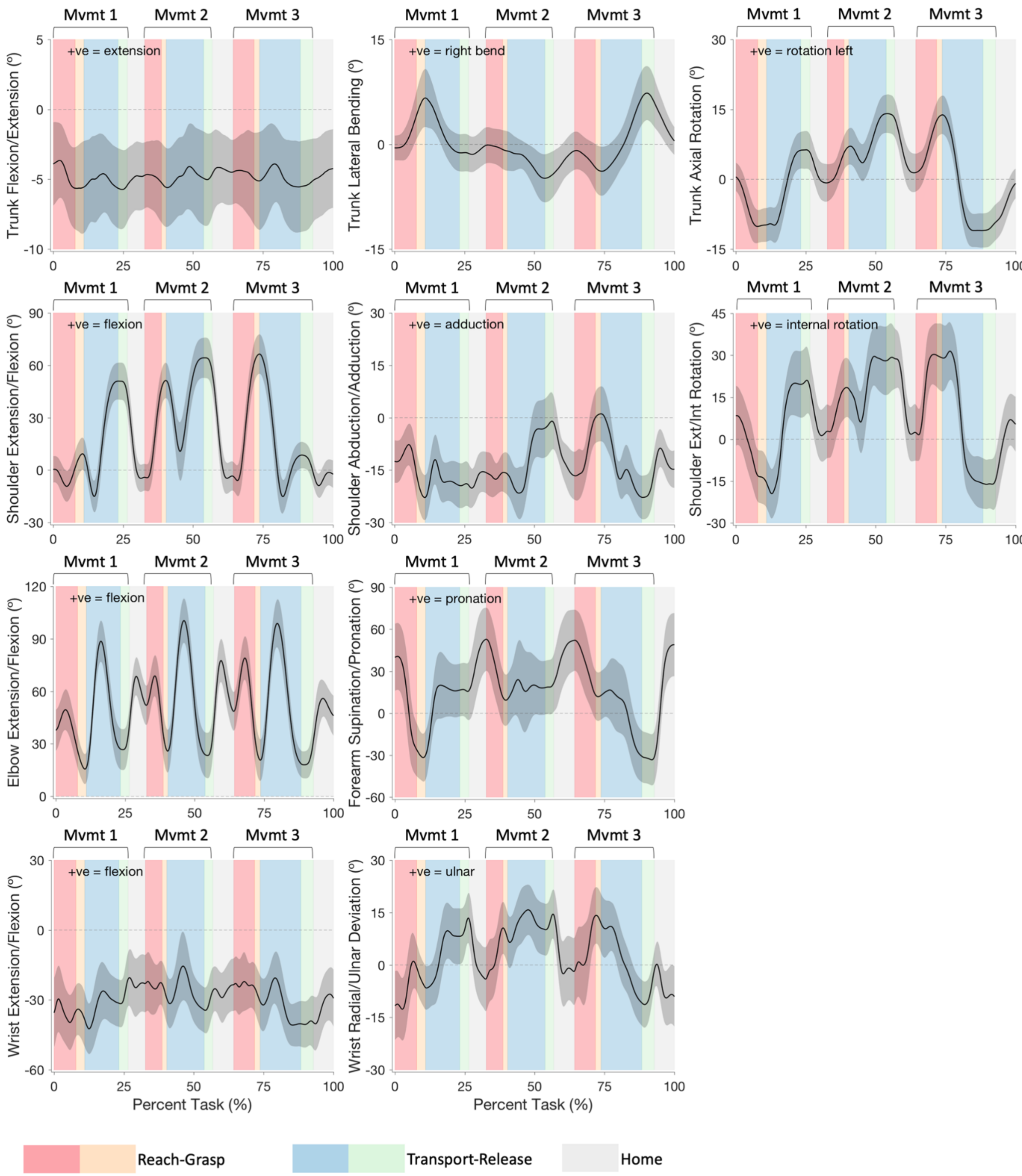

Figure 5-2 Pasta Box Task angular joint trajectories are presented for trunk flexion/extension, lateral bending, and axial rotation; shoulder flexion/extension, abduction/adduction, and internal/external rotation; elbow flexion/extension and forearm pronation/supination; and wrist flexion/extension and ulnar/radial deviation. The group mean is plotted as a solid black line and between-participant standard deviation (SD) as grey shading. Each movement is segmented into reach (red), grasp (orange), transport (blue), and release (green) phases. Times when the hand returned to the "home" starting position are shaded grey. Movements (Mvmt) are indicated above the respective phases in a bracket.

Table 5-2 Pasta Box Task measures for peak angle (degrees), range of motion (degrees), and peak angular velocity (degrees/sec) are presented 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. Data are presented, for movements, as group means and between-participant standard deviations (SD). Average within-participant variability (WPV) is also presented for each measure.

Trunk		Flexion/extension		Lateral bending		Axial rotation	
	Movement	*Mean ± SD*	*WPV*	*Mean ± SD*	*WPV*	*Mean ± SD*	*WPV*
Peak angle (degrees)	1	-2.5 ± 2.7	1.2	6.8 ± 4.1	1.5	6.6 ± 4.0	1.2
	2	-3.0 ± 2.7	1.2	0.4 ± 2.5	1.0	14.4 ± 4.2	1.2
	3	-2.5 ± 2.6	1.2	7.5 ± 3.9	2.2	14.0 ± 4.2	1.2
Range of motion (degrees)	1	5.2 ± 2.2	1.3	8.7 ± 3.2	1.4	17.9 ± 2.5	1.5
	2	3.6 ± 1.1	0.9	5.5 ± 1.8	1.1	15.3 ± 3.1	1.4
	3	4.8 ± 1.3	1.2	11.7 ± 2.8	2.2	25.9 ± 3.7	1.7
Peak angular velocity (degrees/sec)	1	20.9 ± 7.7	5.4	22.7 ± 6.7	5.4	44.7 ± 7.3	6.7
	2	15.8 ± 5.3	3.8	13.6 ± 3.7	3.0	34.2 ± 7.6	4.8
	3	19.9 ± 5.7	4.3	22.1 ± 4.7	6.8	59.9 ± 10.7	8.4

Shoulder		Flexion/extension		Abduction/adduction		Internal/external rotation	
	Movement	*Mean ± SD*	*WPV*	*Mean ± SD*	*WPV*	*Mean ± SD*	*WPV*
Peak angle (degrees)	1	51.5 ± 10.5	2.2	-6.1 ± 4.7	1.5	22.5 ± 11.7	2.2
	2	64.8 ± 11.5	1.9	0.2 ± 7.3	2.2	32.0 ± 11.2	1.9
	3	66.6 ± 11.3	2.1	2.4 ± 6.8	2.2	33.8 ± 11.0	2.0
Range of motion (degrees)	1	68.0 ± 7.7	2.9	19.1 ± 6.5	2.1	42.9 ± 8.6	2.8
	2	70.7 ± 9.8	2.8	24.3 ± 8.3	3.2	31.8 ± 6.5	2.8
	3	83.3 ± 11.8	4.2	27.2 ± 8.9	3.0	52.4 ± 7.7	3.0
Peak angular velocity (degrees/sec)	1	186.4 ± 35.9	15.8	72.3 ± 20.8	9.6	141.2 ± 30.0	16.0
	2	191.1 ± 37.0	14.3	75.8 ± 28.9	11.0	116.2 ± 19.7	14.7
	3	221.3 ± 39.6	20.4	94.7 ± 28.2	11.2	167.6 ± 31.2	20.1

Elbow/Forearm		Flexion/extension		Pronation/supination	
	Movement	*Mean ± SD*	*WPV*	*Mean ± SD*	*WPV*
Peak angle (degrees)	1	89.3 ± 11.8	3.3	42.9 ± 23.3	3.9
	2	101.0 ± 12.7	3.0	53.3 ± 22.5	2.5
	3	100.1 ± 13.9	3.8	53.3 ± 21.9	2.8
Range of motion (degrees)	1	74.2 ± 10.1	3.5	76.2 ± 14.6	5.6
	2	79.5 ± 9.4	3.5	49.8 ± 16.6	5.6
	3	85.5 ± 11.6	4.7	89.5 ± 16.3	6.2
Peak angular velocity (degrees/sec)	1	260.3 ± 48.4	20.6	293.0 ± 63.5	45.6
	2	257.9 ± 43.4	18.6	164.0 ± 51.4	29.8
	3	256.2 ± 43.3	18.4	175.2 ± 42.6	37.0

Wrist		Flexion/extension		Radial/ulnar deviation	
	Movement	*Mean ± SD*	*WPV*	*Mean ± SD*	*WPV*
Peak angle (degrees)	1	-17.6 ± 13.5	4.4	14.9 ± 7.8	2.4
	2	-11.3 ± 13.6	5.1	18.9 ± 7.7	2.7
	3	-12.9 ± 10.5	6.7	16.9 ± 7.6	3.0
Range of motion (degrees)	1	28.5 ± 7.8	4.8	29.6 ± 5.7	3.2
	2	24.8 ± 8.2	5.2	23.4 ± 7.2	3.7
	3	31.3 ± 7.1	7.4	29.2 ± 4.3	3.3
Peak angular velocity (degrees/sec)	1	126.9 ± 29.0	27.0	103.2 ± 36.9	22.8
	2	113.8 ± 33.4	22.8	88.4 ± 21.9	18.5
	3	115.8 ± 33.7	36.9	108.6 ± 23.4	29.7

5.4.2 Cup Transfer Task

Angular joint trajectories for the Cup Transfer Task are shown in Figure 5-3. The mean peak angle, RoM, and peak angular velocity, along with their between-participant SD and within-participant variability, are listed for each movement of the Cup Transfer Task in Table 5-3. The trunk started and ended in a near neutral position for all DoFs. The trunk progressively rotated to the left during Movements 1 and 2 and progressively rotated back towards a neutral position during Movements 3 and 4. Across all trunk DoFs, interacting with the far cup in Movements 2 and 3 required larger RoM than in Movements 1 and 4 (9±4 and 10±4 degrees versus 3±2 and 5±3 degrees for flexion/extension; 7±3 and 6±2 versus 5±2 and 4±1 degrees for lateral bending; 11±3 and 17±4 versus 9±3 and 8±2 degrees for axial rotation) and displayed larger peak angular velocities. Movements 1 (RoM: 62±13 degrees) and 3 (RoM: 73±10 degrees) required large magnitudes of shoulder flexion. Movements 1 and 2 transport, when moving the cups from the right side to the left side, required the shoulder to adduct, and Movements 3 and 4 transport required the shoulder to abduct. Placing and reaching for the near cup on the left side of the box required the greatest amount of shoulder internal rotation during Movements 1 (44±15 degrees) and 4 (46±15 degrees). Every reach and transport displayed a peak in elbow flexion. Greater magnitudes of elbow flexion were required to transport the near cup as opposed to the far cup (Figure 5-3). Moving to the far-left target during Movements 2 and 3 required the elbow to be nearly extended (minimum flexion angle: 11±8 and 9±8 degrees). The top grasp required more forearm pronation (peak angle: 51±21 degrees) and the side grasp forced the forearm to stay in a supinated position (peak angle: –14±19 degrees). The different grasp patterns also required distinct wrist motions: the top grasp required the wrist to be flexed (peak angle: 45±14 degrees) and ulnar-deviated (peak angle: 28±12 degrees), whereas the side grasp forced the wrist into an extended (peak angle: –33±10 degrees) and radial-deviated position (peak angle: –9±9 degrees). Trunk DoFs displayed the lowest peak angular velocity values (11±4 to 40±9 degrees/sec). Shoulder abduction/adduction displayed the lowest angular velocities for shoulder DoFs. Reaching for the cups from the 'Home' position displayed larger shoulder flexion/extension peak angular velocities (222±55 degrees/sec), whereas changing the grasp to pick up the next cup in Movements 2 and 4 displayed larger shoulder internal/external rotation angular velocities (168±33 degrees/sec). For the elbow and wrist joints, movement in flexion/extension displayed larger angular velocities than forearm pronation/supination or radial/ulnar deviation.

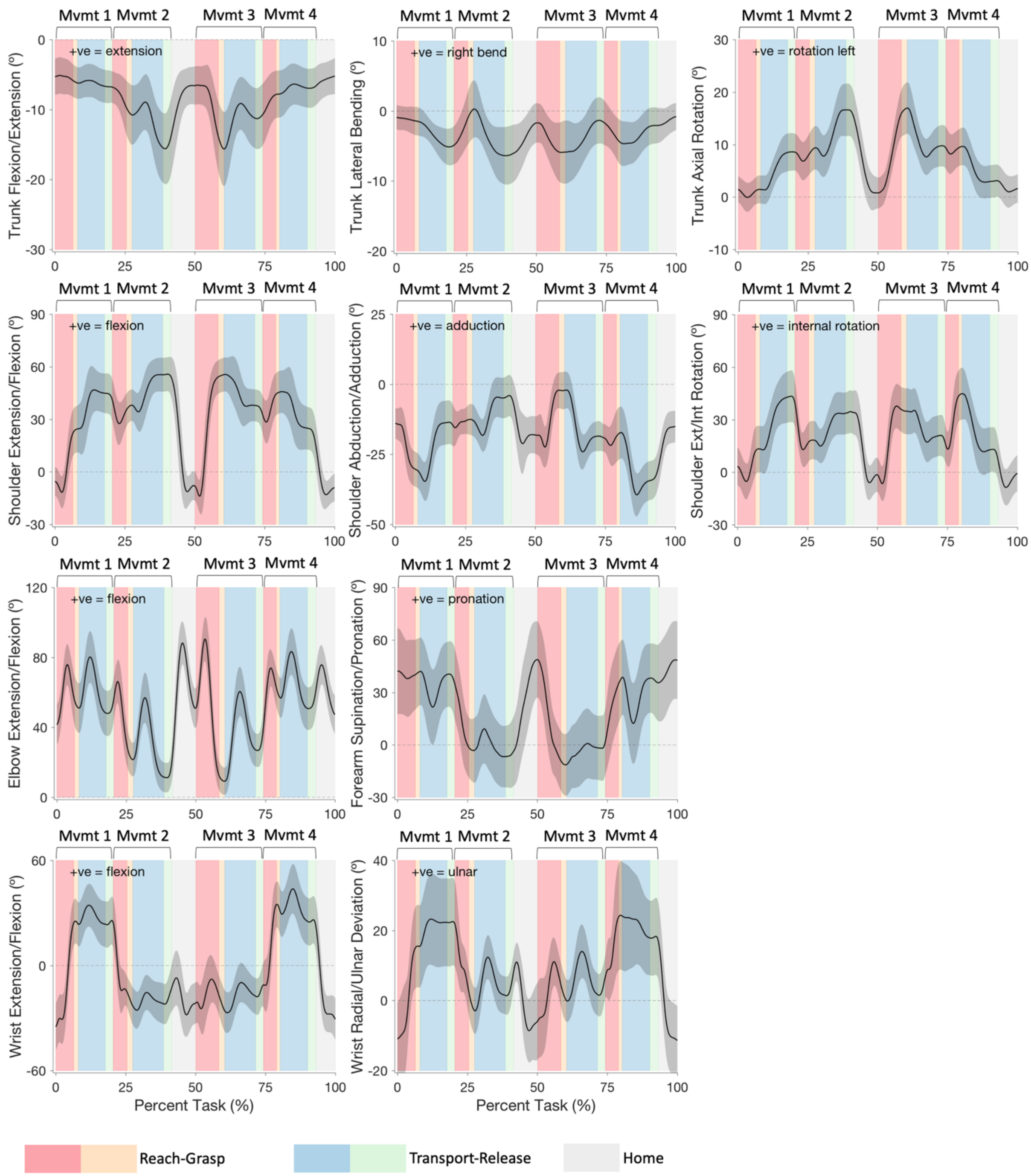

Figure 5-3 Cup Transfer Task angular joint trajectories are presented for trunk flexion/extension, lateral bending, and axial rotation; shoulder flexion/extension, abduction/adduction, and internal/external rotation; elbow flexion/extension and forearm pronation/supination; and wrist flexion/extension and ulnar/radial deviation. The group mean is plotted as a solid black line and between-participant standard deviations (SD) as grey shading. Each movement is segmented into reach (red), grasp (orange), transport (blue), and release (green) phases. Times when the hand returned to the "home" starting position are shaded grey. Movements (Mvmt) are indicated above the respective phases in a bracket.

Table 5-3 Cup Transfer Task measures for peak angle (degrees), range of motion (degrees), and peak angular velocity (degrees/sec) are presented 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. Data are presented, for movements, as group means and between-participant standard deviations (SD). Average within-participant variability (WPV) is also presented for each measure.

Trunk		Flexion/extension		Lateral bending		Axial rotation	
	Movement	*Mean ± SD*	*WPV*	*Mean ± SD*	*WPV*	*Mean ± SD*	*WPV*
Peak angle (degrees)	1	-4.4 ± 2.5	1.1	-0.6 ± 1.8	1.1	8.9 ± 3.6	1.3
	2	-6.4 ± 2.5	1.2	0.4 ± 4.1	1.2	17.0 ± 4.9	1.3
	3	-5.8 ± 2.8	1.1	-0.7 ± 3.1	1.1	17.1 ± 4.9	1.3
	4	-5.8 ± 2.7	1.1	-1.1 ± 2.9	1.0	10.2 ± 3.8	1.0
Range of motion (degrees)	1	3.1 ± 1.5	0.9	4.7 ± 1.9	1.0	9.3 ± 2.5	1.3
	2	9.4 ± 3.8	1.3	7.4 ± 2.5	1.3	10.6 ± 2.7	1.3
	3	10.0 ± 3.8	1.4	6.0 ± 1.9	1.1	16.6 ± 4.0	1.7
	4	4.9 ± 2.6	1.0	3.9 ± 1.4	0.8	7.8 ± 2.3	0.9
Peak angular velocity (degrees/sec)	1	11.8 ± 3.8	3.8	10.6 ± 4.1	2.3	22.0 ± 4.3	3.9
	2	24.2 ± 6.9	3.8	17.6 ± 6.2	3.6	29.3 ± 7.1	4.4
	3	28.8 ± 9.1	4.5	15.6 ± 3.7	3.8	39.9 ± 8.9	5.5
	4	14.3 ± 5.0	4.6	11.4 ± 3.2	2.9	23.6 ± 6.9	3.8
Shoulder		Flexion/extension		Abduction/adduction		Internal/external rotation	
	Movement	*Mean ± SD*	*WPV*	*Mean ± SD*	*WPV*	*Mean ± SD*	*WPV*
Peak angle (degrees)	1	49.0 ± 14.2	2.7	-8.7 ± 4.9	2.1	44.1 ± 14.7	2.6
	2	57.2 ± 10.3	1.8	-2.2 ± 6.6	2.5	42.1 ± 13.4	2.1
	3	57.8 ± 11.0	1.9	-0.6 ± 5.9	2.5	40.9 ± 13.5	3.0
	4	49.3 ± 14.3	3.2	-14.5 ± 6.9	2.4	45.8 ± 14.5	2.7
Range of motion (degrees)	1	61.5 ± 13.2	3.4	26.8 ± 6.9	2.8	50.2 ± 13.8	3.5
	2	31.1 ± 6.7	2.8	18.2 ± 5.5	2.8	31.4 ± 6.8	2.8
	3	73.0 ± 10.1	2.8	27.8 ± 8.5	3.2	48.3 ± 12.1	3.8
	4	30.3 ± 9.1	3.3	25.6 ± 5.8	3.0	38.7 ± 9.5	3.2
Peak angular velocity (degrees/sec)	1	136.0 ± 40.2	14.1	77.6 ± 21.7	9.4	111.6 ± 53.5	16.4
	2	100.4 ± 27.3	13.4	60.8 ± 15.7	10.3	168.0 ± 32.9	20.1
	3	221.8 ± 55.0	22.9	94.5 ± 33.0	11.7	178.7 ± 54.2	21.6
	4	106.3 ± 24.7	13.4	73.7 ± 17.4	9.3	151.5 ± 36.0	19.0

Elbow/Forearm		Flexion/extension		Pronation/supination	
	Movement	*Mean ± SD*	*WPV*	*Mean ± SD*	*WPV*
Peak angle (degrees)	1	84.0 ± 12.0	3.1	50.9 ± 21.0	3.2
	2	69.7 ± 11.3	3.0	35.5 ± 19.3	3.4
	3	91.8 ± 12.3	3.0	49.8 ± 21.7	3.0
	4	84.2 ± 13.0	2.7	42.1 ± 20.9	3.3
Range of motion (degrees)	1	44.4 ±9.5	3.8	31.6 ± 12.5	4.5
	2	59.1 ± 7.8	3.6	45.6 ± 12.3	5.6
	3	82.9 ± 8.9	3.4	63.7 ± 11.4	5.8
	4	46.1 ± 5.6	3.3	44.7 ± 9.3	5.0
Peak angular velocity (degrees/sec)	1	165.7 ± 39.4	15.4	111.0 ± 21.7	22.3
	2	195.7 ± 39.3	19.7	175.3 ± 42.3	36.3
	3	270.3 ± 51.9	21.3	190.1 ± 46.0	46.1
	4	216.0 ± 37.3	18.5	179.2 ± 59.4	26.3
Wrist		Flexion/extension		Radial/ulnar deviation	
	Movement	*Mean ± SD*	*WPV*	*Mean ± SD*	*WPV*
Peak angle (degrees)	1	36.4 ± 12.2	4.0	25.5 ± 12.0	3.2
	2	27.3 ± 13.2	3.5	24.1 ± 10.2	3.1
	3	0.4 ± 14.4	7.7	15.7 ± 7.2	2.9
	4	45.1 ± 14.0	3.7	27.8 ± 12.2	2.8
Range of motion (degrees)	1	74.5 ± 14.2	6.0	38.4 ± 9.5	4.0
	2	55.7 ± 7.3	4.8	28.0 ± 7.2	3.8
	3	33.4 ± 10.5	7.6	24.6 ± 6.0	3.8
	4	61.2 ± 10.2	6.6	23.3 ± 6.2	4.1
Peak angular velocity (degrees/sec)	1	272. 1 ± 69.7	38.7	133.3 ± 37.7	23.4
	2	263.2 ± 71.1	40.4	121.5 ± 40.6	22.7
	3	155.9 ± 59.8	47.0	113.7 ± 35.3	25.8
	4	288.5 ± 61.5	41.0	123.8 ± 35.8	25.6

5.4.3 Variability and Intra-Rater Reliability

For both tasks, between-participant variability was typically larger than within-participant variability (Tables 5-2 and 5-3). For the trunk DoFs, the absolute between-participant variability was below 5 degrees for peak angle and RoM. The majority of the remaining DoFs displayed an absolute between-participant variability of over 5 degrees. Forearm pronation/supination displayed the largest between-participant variability. The majority of DoFs exhibited a within-participant variability for peak angle and RoM that was below 5 degrees.

For each kinematic measure, values for ICC with 95% confidence intervals, SEM, and MDC are shown in Table 5-4 (Pasta Box Task) and Table 5-5 (Cup Transfer Task). For the Pasta Box Task, 52% of measures displayed ICC values above 0.75, and 23% above 0.90, therefore having reasonable agreement for clinical assessments (Portney and Watkins, 2009). The highest reliability was observed for shoulder and elbow flexion/extension. ICC values below 0.75 were mostly observed for trunk and wrist DoFs. For the Cup Transfer Task, 54% of measures displayed ICC values above 0.75, and 28% above 0.90. Best reliability was observed for trunk axial rotation and all three DoFs at the shoulder. Reliability for elbow flexion/extension was not as high as for the Pasta Box Task. Forearm pronation/supination peak angle displayed the greatest SEM values (11 to 15 degrees) across both tasks. When excluding this DoF, all SEM values for peak angle and RoM were below 8 degrees and 11 degrees for the Pasta Box and Cup Transfer Tasks, respectively. MDC values for peak angle and RoM were below 35 and 41 degrees, with 21 and 29 measures below 10 degrees for the Pasta Box and Cup Transfer Tasks, respectively.

Table 5-4 For each Pasta Box Task movement, repeatability analysis was performed on peak angle, range of motion, and peak angular velocity 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 radial/ulnar deviation. Repeatability measures include intra-class correlation (ICC) with corresponding 95% confidence intervals, standard error of measurement (SEM), and minimal detectable change (MDC). ICC values above 0.90 are presented in bold. ICC values below 0.75 are presented in italics. ICC values that failed the F-test ($p > 0.05$) are presented with an asterisk (*), indicating the validity of the ICC may be compromised for this result.

Trunk		Flexion/extension			Lateral bending			Axial rotation		
	Movement	*ICC*	*SEM*	*MDC*	*ICC*	*SEM*	*MDC*	*ICC*	*SEM*	*MDC*
Peak angle (degrees)	1	*-0.08 (-3.36-0.73)**	1.9	5.3	0.76 (0.02-0.94)	2.7	7.4	*0.70 (-0.21-0.93)*	2.9	8.1
	2	*0.34 (-1.66-0.84)**	2.3	6.3	0.87 (0.47-0.97)	1.1	2.9	*0.63 (-0.50-0.91)**	3.4	9.6
	3	*0.19 (-2.27-0.80)**	1.8	4.9	0.75 (0.01-0.94)	2.9	8.0	*0.52 (-0.95-0.88)**	3.7	10.2
Range of motion (degrees)	1	0.81 (0.22-0.95)	1.5	4.0	*0.54 (-0.86-0.89)**	2.4	6.6	*0.45 (-1.21-0.86)**	2.9	8.0
	2	0.84 (0.34-0.96)	0.7	2.0	0.84 (0.34-0.96)	0.9	2.6	*0.68 (-0.27-0.92)**	2.2	6.2
	3	*0.01 (-2.98-0.76)**	1.3	3.5	*0.62 (-0.55-0.90)**	2.6	7.2	*0.73 (-0.07-0.93)*	3.4	9.4
Peak angular velocity (degrees/sec)	1	*0.47 (-1.13-0.87)**	7.7	21.3	*0.66 (-0.35-0.93)**	4.8	13.4	*0.11 (-2.57-0.78)**	6.1	16.8
	2	0.89 (0.55-0.97)	3.4	9.6	*0.60 (-0.62-0.90)**	2.2	6.1	**0.90 (0.59-0.97)**	3.3	9.3
	3	*0.48 (-1.10-0.87)**	5.2	14.5	*0.60 (-0.63-0.90)**	4.3	11.9	*0.55 (-0.81-0.89)**	7.2	20.0

Shoulder		Flexion/extension			Abduction/adduction			Internal/external rotation		
	Movement	*ICC*	*SEM*	*MDC*	*ICC*	*SEM*	*MDC*	*ICC*	*SEM*	*MDC*
Peak angle (degrees)	1	0.80 (0.20-0.95)	6.6	18.2	*0.26 (-1.97-0.82)**	3.9	10.9	0.75 (-0.02-0.94)	7.1	19.6
	2	**0.91 (0.64-0.98)**	5.5	15.3	*0.54 (-0.85-0.89)**	5.8	16.1	*0.69 (-0.26-0.92)*	8.2	22.7
	3	**0.90 (0.60-0.98)**	5.8	16.0	*0.57 (-0.73-0.89)**	5.4	15.1	*0.45 (-1.21-0.86)**	7.7	21.4
Range of motion (degrees)	1	**0.96 (0.85-0.99)**	3.3	9.2	0.86 (0.44-0.97)	3.7	10.1	**0.95 (0.80-0.99)**	3.6	10.0
	2	**0.97 (0.88-0.99)**	2.8	7.8	0.79 (0.16-0.95)	5.9	16.3	0.78 (0.13-0.95)	5.9	16.5
	3	**0.93 (0.74-0.98)**	4.4	12.1	*0.10 (-2.64-0.78)**	8.9	24.5	**0.92 (0.68-0.98)**	3.9	10.7
Peak angular velocity (degrees/sec)	1	**0.95 (0.79-0.99)**	14.5	40.2	0.83 (0.32-0.96)	12.0	33.1	0.82 (0.28-0.96)	17.2	47.7
	2	**0.97 (0.89-0.99)**	9.3	25.9	0.84 (0.35-0.96)	16.9	46.8	*0.53 (-0.87-0.88)**	16.4	45.5
	3	**0.95 (0.80-0.99)**	12.1	33.6	*0.69 (-0.27-0.92)*	17.0	47.0	*0.71 (-0.18-0.93)*	21.6	59.9

Elbow/Forearm		Flexion/extension			Pronation/supination		
	Movement	*ICC*	*SEM*	*MDC*	*ICC*	*SEM*	*MDC*
Peak angle (degrees)	1	0.83 (0.32-0.96)	5.2	14.3	*0.70 (-0.2-0.93)*	12.3	34.2
	2	0.85 (0.41-0.96)	6.1	16.9	*0.60 (-0.62-0.90)**	11.9	32.9
	3	0.79 (0.14-0.95)	6.2	17.2	*0.66 (-0.36-0.92)**	10.6	29.3
Range of motion (degrees)	1	0.77 (0.06-0.94)	5.7	15.8	**0.92 (0.68-0.98)**	8.2	22.6
	2	**0.92 (0.67-0.98)**	3.6	10.1	**0.95 (0.79-0.99)**	5.9	16.3
	3	**0.91 (0.62-0.98)**	4.9	13.7	0.89 (0.57-0.97)	5.2	14.5
Peak angular velocity (degrees/sec)	1	0.85 (0.39-0.96)	24.0	66.5	0.88 (0.51-0.97)	36.9	102.2
	2	**0.95 (0.80-0.99)**	14.6	40.4	**0.90 (0.60-0.98)**	21.8	60.4
	3	**0.96 (0.85-0.99)**	11.7	32.5	*0.67 (-0.33-0.92)**	27.6	76.5
Wrist		Flexion/extension			Radial/ulnar deviation		
	Movement	*ICC*	*SEM*	*MDC*	*ICC*	*SEM*	*MDC*
Peak angle (degrees)	1	*0.45 (-1.21-0.86)**	8.7	24.2	*-0.43 (-4.77-0.64)**	7.3	20.1
	2	*0.65 (-0.39-0.91)**	7.8	21.5	*-0.77 (-6.12-0.56)**	7.3	20.2
	3	*0.69 (-0.26-0.92)**	6.6	18.3	*0.25 (-2.01-0.81)**	6.8	18.7
Range of motion (degrees)	1	0.89 (0.57-0.97)	2.9	8.0	*-0.27 (-3.90-0.70)**	4.2	11.7
	2	0.89 (0.54-0.97)	4.0	11.1	*0.69 (-0.24-0.92)*	3.9	10.7
	3	*0.67 (-0.33-0.92)**	5.0	13.9	*0.50 (-1.01-0.88)**	2.6	7.3
Peak angular velocity (degrees/sec)	1	**0.94 (0.74-0.98)**	13.5	37.4	**0.90 (0.61-0.98)**	15.9	44.1
	2	0.79 (0.16-0.95)	16.2	44.8	*0.25 (-2.03-0.81)**	16.8	46.5
	3	0.85 (0.39-0.96)	12.2	33.8	**0.91 (0.63-0.98)**	13.3	37.0

Table 5-5 For each Cup Transfer Task movement, repeatability analysis was performed on peak angle, range of motion, and peak angular velocity 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 radial/ulnar deviation. Repeatability measures include intra-class correlation (ICC) with corresponding 95% confidence intervals, standard error of measurement (SEM), and minimal detectable change (MDC). ICC values above 0.90 are presented in bold. ICC values below 0.75 are presented in italics. ICC values that failed the F-test (p > 0.05) are presented with an asterisk (*), indicating the validity of the ICC may be compromised for this result.

Trunk		Flexion/extension			Lateral bending			Axial rotation		
	Movement	*ICC*	*SEM*	*MDC*	*ICC*	*SEM*	*MDC*	*ICC*	*SEM*	*MDC*
Peak angle (degrees)	1	*-0.10 (-3.07-0.75)**	2.8	7.9	0.82 (0.28-0.96)	1.1	3.0	*0.25 (-2.02-0.81)**	3.6	9.9
	2	*0.38 (-1.49-0.85)**	2.8	7.8	**0.91 (0.64-0.98)**	1.6	4.6	*0.70 (-0.20-0.93)*	3.6	10.0
	3	*0.62 (-0.52-0.91)**	2.3	6.4	**0.93 (0.73-0.98)**	1.0	2.8	*0.72 (-0.14-0.93)*	3.6	9.9
	4	*0.63 (-0.48-0.91)**	2.5	7.1	0.89 (0.54-0.97)	1.2	3.4	*0.51 (-0.97-0.88)**	3.5	9.7
Range of motion (degrees)	1	*0.39 (-1.44-0.85)**	1.1	2.9	*0.70 (-0.22-0.93)*	1.2	3.2	**0.90 (0.61-0.98)**	1.4	4.0
	2	*0.73 (-0.08-0.93)*	1.9	5.3	**0.94 (0.76-0.99)**	1.0	2.9	**0.91 (0.65-0.98)**	1.2	3.4
	3	*0.48 (-1.08-0.87)**	2.2	6.0	*0.52 (-0.95-0.88)**	1.7	4.8	**0.95 (0.80-0.99)**	2.0	5.7
	4	*0.58 (-0.68-0.90)**	1.4	3.8	*0.60 (-0.60-0.90)**	1.0	2.8	**0.91 (0.63-0.98)**	1.2	3.2
Peak angular velocity (degrees/sec)	1	0.89 (0.55-0.97)	2.2	6.0	0.81 (0.22-0.95)	1.4	3.9	0.89 (0.57-0.97)	2.7	7.6
	2	*0.58 (-0.70-0.90)**	5.6	15.7	**0.94 (0.77-0.99)**	1.9	5.2	**0.91 (0.63-0.98)**	3.1	8.6
	3	*0.71 (-0.18-0.93)*	5.4	15.0	*0.24 (-2.07-0.81)**	2.5	6.9	**0.94 (0.77-0.99)**	3.0	8.2
	4	0.79 (0.14-0.95)	1.7	4.8	*0.06 (-2.77-0.77)**	2.2	6.0	0.89 (0.55-0.97)	3.3	9.3

Shoulder		Flexion/extension			Abduction/adduction			Internal/external rotation		
	Movement	*ICC*	*SEM*	*MDC*	*ICC*	*SEM*	*MDC*	*ICC*	*SEM*	*MDC*
Peak angle (degrees)	1	**0.95 (0.79-0.99)**	5.9	16.3	*0.64 (-0.46-0.91)**	3.7	10.3	0.80 (0.19-0.95)	8.9	24.6
	2	**0.90 (0.58-0.97)**	6.1	16.9	*0.42 (-1.35-0.86)**	5.0	14.0	0.78 (0.13-0.95)	8.4	23.3
	3	**0.91 (0.66-0.98)**	6.0	16.5	*0.34 (-1.67-0.84)**	5.5	15.2	*0.57 (-0.73-0.89)**	9.4	26.1
	4	**0.97 (0.86-0.99)**	5.3	14.7	*0.56 (-0.76-0.89)**	5.0	13.8	*0.74 (-0.06-0.94)*	9.7	26.9
Range of motion (degrees)	1	**0.98 (0.92-1.00)**	3.4	9.4	0.85 (0.41-0.96)	4.1	11.3	**0.95 (0.80-0.99)**	5.5	15.1
	2	0.75 (0.01-0.94)	3.6	9.9	**0.94 (0.75-0.98)**	2.4	6.7	0.84 (0.33-0.96)	4.5	12.5
	3	**0.95 (0.79-0.99)**	4.1	11.4	0.89 (0.58-0.97)	4.2	11.5	0.84 (0.37-0.96)	7.5	20.7
	4	0.86 (0.43-0.97)	5.5	15.2	**0.90 (0.60-0.98)**	2.7	7.6	0.86 (0.42-0.96)	5.4	15.0
Peak angular velocity (degrees/sec)	1	**0.97 (0.87-0.99)**	11.6	32.1	**0.97 (0.89-0.99)**	5.9	16.2	**0.96 (0.83-0.99)**	19.0	52.7
	2	**0.90 (0.58-0.97)**	12.1	33.4	**0.94 (0.76-0.99)**	7.0	19.3	**0.93 (0.71-0.98)**	17.2	47.7
	3	**0.93 (0.71-0.98)**	27.0	75.0	**0.94 (0.74-0.98)**	13.1	36.3	0.85 (0.38-0.96)	37.7	104.6
	4	0.84 (0.36-0.96)	16.1	44.5	0.83 (0.30-0.96)	11.4	31.7	0.85 (0.39-0.96)	22.3	61.8

Elbow/Forearm		Flexion/extension			Pronation/supination		
	Movement	*ICC*	*SEM*	*MDC*	*ICC*	*SEM*	*MDC*
Peak angle (degrees)	1	*-0.13 (-3.55-0.72)**	7.9	21.8	*0.40 (-1.40-0.85)**	14.6	40.4
	2	*0.40 (-1.42-0.85)**	7.4	20.6	0.82 (0.26-0.95)	10.7	29.8
	3	*0.55 (-0.80-0.89)**	7.0	19.5	*0.59 (-0.67-0.90)**	11.7	32.5
	4	*0.67 (-0.31-0.92)**	8.0	22.3	0.75 (0.00-0.94)	11.3	31.4
Range of motion (degrees)	1	*0.65 (-0.41-0.91)**	5.8	16.1	*0.53 (-0.89-0.88)**	8.7	24.2
	2	*0.64 (-0.46-0.91)**	4.2	11.6	*0.54 (-0.86-0.89)**	9.4	26.2
	3	0.84 (0.36-0.96)	4.1	11.4	*0.24 (-2.06-0.81)**	11.4	31.7
	4	*0.68 (-0.29-0.92)**	4.0	11.1	*0.74 (-0.06-0.94)*	5.0	13.8
Peak angular velocity (degrees/sec)	1	0.84 (0.34-0.96)	21.4	59.4	*0.74 (-0.04-0.94)*	24.3	67.4
	2	**0.92 (0.67-0.98)**	19.6	54.3	*0.64 (-0.46-0.91)**	20.0	55.3
	3	0.89 (0.55-0.97)	25.1	69.5	0.81 (0.25-0.95)	28.2	78.1
	4	**0.97 (0.87-0.99)**	15.0	41.4	0.83 (0.30-0.96)	25.9	71.8

Wrist		Flexion/extension			Radial/ulnar deviation		
	Movement	*ICC*	*SEM*	*MDC*	*ICC*	*SEM*	*MDC*
Peak angle (degrees)	1	*0.44 (-1.26-0.86)**	8.5	23.5	*0.51 (-0.96-0.88)**	9.2	25.6
	2	*0.32 (-1.75-0.83)**	9.1	25.4	*0.36 (-1.57-0.84)**	8.9	24.8
	3	*0.72 (-0.12-0.93)*	9.4	26.2	*0.53 (-0.88-0.88)**	6.1	17.0
	4	*0.40 (-1.43-0.85)**	10.2	28.2	*0.48 (-1.08-0.87)**	9.4	26.1
Range of motion (degrees)	1	**0.97 (0.87-0.99)**	3.7	10.3	*0.74 (-0.05-0.94)*	6.7	18.6
	2	0.83 (0.31-0.96)	2.9	7.9	0.77 (0.09-0.94)	5.1	14.0
	3	*0.74 (-0.06-0.94)*	6.5	18.1	0.87 (0.45-0.97)	3.3	9.2
	4	*0.72 (-0.13-0.93)*	6.2	17.3	*0.62 (-0.55-0.91)**	4.6	12.8
Peak angular velocity (degrees/sec)	1	**0.98 (0.91-1.00)**	16.1	44.6	*0.52 (-0.93-0.88)**	31.3	86.8
	2	**0.92 (0.67-0.98)**	25.3	70.0	*0.57 (-0.72-0.89)**	28.2	78.3
	3	*0.50 (-1.00-0.88)**	44.3	122.7	**0.92 (0.67-0.98)**	14.0	38.9
	4	**0.90 (0.58-0.97)**	32.9	91.3	*0.73 (-0.08-0.93)*	22.7	62.9

5.5 Discussion

This study established a normative dataset of 3D angular joint kinematics for two standardized functional tasks, the Pasta Box Task and Cup Transfer Task, with generally good test-retest reliability. The joint kinematic results provided insights into the specific task requirements for each functional movement.

5.5.1 Angular Joint Motion

Overall, minimal trunk movement was required to complete the tasks. However, the Pasta Box Task required a greater range of trunk lateral bending and trunk axial rotation compared to flexion/extension. For the Cup Transfer Task, movement of the far cup required greater RoM across all trunk DoFs. While trunk movement is not commonly reported in upper limb analyses of non-disabled individuals (Alt Murphy et al., 2006; Rab et al., 2002), its assessment is important when studying upper limb impairments. When hand function is impaired by neuromuscular or musculoskeletal injury, proximal joints and the trunk are likely to display compensatory motion to successfully complete a task (Hebert et al., 2014; Hebert and Lewicke, 2012). Therefore, inclusion of trunk motion in non-disabled analyses can serve as a benchmark for comparison to impaired function.

Across all shoulder DoFs, for the Pasta Box Task, reaching from the top shelf of the cart to the side table required the largest RoM, highlighting how cross-body movements demand large joint exertions. For the Cup Transfer Task, Movements 1 and 3, where the hand left a position at the near edge of the cart ("Home" in Figure 5-3), required the largest RoM. The varying requirements across movements indicate how differing shelf heights or object locations in relation to the edge of a counter, as in a standard kitchen, highly influences the joint range needed to complete ADLs.

Elbow flexion/extension displayed some of the largest angular velocities among all DoFs for both tasks. Angular velocity, a predictor of an individual's muscle power (Lobo-Prat et al., 2012), is valuable when studying populations with impairments as it gives insight into the adequate functioning and force production of muscles (Chang et al., 2005; Flash and Hogans, 1985). Mackey et al. found that angular velocities were reduced in children with cerebral palsy (Mackey et al., 2006), indicating muscle fatigue or weakness could be present with upper limb deficits. Forearm pronation/supination RoM during the Pasta Box Task displayed the largest amount of between- and within-participant variability during transport (Table 5-2). The task standardized the movement requirements by setting a specific starting position for the hand and defining precise pick-up and drop-off locations for the objects; however, the orientation in which the box of pasta was grasped, carried, and placed was not enforced, allowing individual grasp strategies. The tilt of the box of pasta during the transport phase would in turn change the angle of pronation or supination of the forearm, thereby explaining the larger between-participant variability observed in this task.

Clear differences, based on task requirements, were observed in wrist angular joint trajectories. Throughout the Pasta Box Task, interacting with the box of pasta forced the wrist into an extended position. For the Cup Transfer Task, the top grasp required the wrist to be in a flexed position and the side grasp in a slightly extended position. This clear distinction of wrist movement between different grasp patterns is an example of how 3D kinematic analyses, along with these specific tasks, are capable of quantifying small changes in movement strategies. This level of sensitivity might be useful when assessing novel prosthetic technologies incorporating wrist movement as subtle shifts in wrist position would be expected to influence proximal joint motion. Current clinical assessments for prosthetic technologies are typically not sensitive enough to quantitatively detect subtleties in wrist movement (Hebert and Lewicke, 2012; Lindner et al., 2009; Resnik et al., 2013a).

5.5.2 Intra-Rater Reliability

Overall, for both tasks, just over half of the measures presented good reliability and about a quarter of the measures presented excellent reliability. For the Pasta Box Task, measures for the shoulder and elbow DoFs in the sagittal plane were the most reliable. Trunk, forearm, and wrist DoFs were not as reliable, possibly due to the lack of standardization regarding the exact position where the participant had to stand and the orientation in which the participants had to hold the box of pasta. If the participant selected different end-point movement strategies to complete the task, this would increase trial-to-trial variability and decrease reliability (Reid et al., 2010). In addition, trunk movement was minimal for the presented tasks, exhibiting small RoM and standard deviations, which would lead to lower ICC values (Weir, 2005). This is consistent with previous literature, where Engdahl and Gates as well as Jaspers et al. indicated lower reliability at trunk and wrist DoFs (Engdahl and Gates, 2018; Jaspers et al., 2011a). For the Cup Transfer Task, the shoulder DoFs displayed the best reliability. Overall, the Cup Transfer Task presented slightly higher reliability than the Pasta Box Task, potentially due to its more constricted movements. SEM and MDC values for peak angle and RoM were in accordance with previous studies examining peak angles and RoM at the upper body. In comparison to the present study where SEM values were below 11 degrees, Engdahl and Gates and Jaspers et al. reported SEM values below 9 degrees (Engdahl and Gates, 2018; Jaspers et al., 2011a). The present MDC values for trunk DoFs were less than 10 degrees, which is consistent with Engdahl and Gates. Overall, for shoulder, elbow, and wrist DoFs, the present MDC values were 5 degrees greater than those presented by Engdahl and Gates (Engdahl and Gates, 2018). It should be noted that the slightly higher SEM and MDC values in the present study can be explained by the inclusion of all upper body DoFs, compared to studies that exclude many elbow and wrist DoFs exhibiting inconsistent results across participants (Engdahl and Gates, 2018) .

5.5.3 Limitations

The cluster-based marker set used here for calculating angular joint kinematics relies on a specific anatomical pose that does not require the identification of anatomical landmarks (Boser et al., 2018), making the marker set relatively easy to use. However, due to its calibration technique, there are potential offsets when comparing against a traditional anatomical marker set (Hebert et al., 2014; Petuskey et al., 2007; Rab et al., 2002), especially for trunk flexion/extension, elbow and wrist DoFs. As a consequence, literature to directly compare our peak angle results against is limited. Despite this limitation, the marker set by Boser et al. presented low variability and good intra-rater reliability (Boser et al., 2018), making it a viable clinical tool for assessing kinematics in impaired populations. Another limitation may be that we did not normalize task setup relative to body height, potentially contributing to higher between-participant variability in our results. This choice was, however, driven by our goal to ecologically represent the natural variability in real-world activities, as would be encountered at a “standard” counter height.

5.6 Conclusion

This study reported on the 3D angular joint kinematics of the upper body required to complete two standardized functional tasks. Differences in trunk kinematics were observed based on the requirements of the specific movements. Participants converged on similar shoulder and elbow movement strategies, which exhibited smaller variability bands and higher intra-rater reliability. Forearm and wrist DoFs, which are to a greater degree responsible for specific end-point movement, showed larger variability and lower intra-rater reliability. Overall, this study provides a comprehensive upper body kinematic dataset that can be used for comparing populations with impairments and quantitatively assessing movement compensations.

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Chapter 6. Compensatory Strategies of Body-Powered Prosthesis Users Reveal Primary Reliance on Trunk Motion and Relation to Skill Level

The material presented in this chapter has been published in the article:

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The content of this chapter includes the material presented in the publication and an addition in the discussion section. The text formatting was done according to University of Alberta requirements. Parts of this work have also been presented at scientific conferences including the *Myoelectric Controls Symposium (MEC),* held on August 15 to August 18, 2017, in Fredericton, Canada, *The Spotlight on Research Breakfast*, held on November 22, 2017, in Edmonton, Canada, and *The XXVII Congress of the International Society of Biomechanics,* in conjunction with *The 43rd Annual Meeting of the American Society of Biomechanics,* held on July 31 to August 4, 2019, in Calgary, Canada.

6.1 Abstract

Background: While body-powered prostheses are commonly used, the compensatory strategies required to operate body-powered devices are not well understood. Kinematic assessment in addition to standard clinical tests can give a comprehensive evaluation of prosthesis user function and skill. This study investigated the movement compensations of body-powered prosthesis users and determined whether a correlation is present between compensatory strategies and skill level, as measured by a standard clinical test.

Methods: Five transradial body-powered prosthesis users completed two standardized upper limb tasks. A 12-camera motion capture system was used to obtain three-dimensional angular kinematics for eight degrees of freedom at the trunk, shoulder, and elbow. Range of motion was compared to a normative dataset. Pearson's correlation was used to assess the relationship between the Activities Measure for Upper Limb Amputees and range of motion for each degree of freedom.

Findings: Participants displayed a statistically significant ($P < .05$) increase in range of motion at the trunk for both tasks. Shoulder flexion/extension range of motion was significantly reduced ($P < .05$) compared to normative values, but shoulder abduction/adduction range of motion did not show a consistent difference compared to norms. Skill level was correlated with range of motion for specific degrees of freedom at the trunk, shoulder, and elbow.

Interpretation: Body-powered prosthesis users compensated with trunk movement and showed reduced motion for shoulder flexion/extension, with relatively normal shoulder abduction/adduction. Skill level was correlated with angular kinematic strategies, which may allow targeting of specific therapeutic interventions for reducing compensatory movements.

6.2 Introduction

Various types of prosthetic devices can be used to restore arm function following amputation. Body-powered prostheses are controlled by active body movements via a harness and cable system, and myoelectric prostheses are controlled via electromyographic (EMG) signals from muscles in the residual limb. Although more recent emphasis has been placed on myoelectric technologies with the goal of restoring more natural movement patterns (Hutchinson, 2014), in North America the most commonly prescribed prostheses are still body-powered (Huang et al., 2001), with myoelectric devices often seen as exceeding the standard of care (Stevens and Highsmith, 2017).

Specific characteristics of the prosthetic technology have a direct effect on overall body movements of the user (Bertels et al., 2009). Compensations (defined as an increase in RoM) or movement impairments (defined as a decrease in RoM) relative to non-disabled movement have been demonstrated in users of myoelectric prosthetic devices with limited hand grasp dexterity and lack of wrist motion (Bouwsema et al., 2010; Carey et al., 2008). Myoelectric prosthesis users show compensatory strategies of increased motion at the trunk (Carey et al., 2008; Hussaini et al., 2017; Major et al., 2014; Metzger et al., 2012) and shoulder (Bertels et al., 2009; Major et al., 2014; Metzger et al., 2012). Only a few studies have examined movement strategies in body-powered prosthesis users (Abd Razak et al., 2013; Carey et al., 2009; Hebert and Lewicke, 2012) and suggest that body-powered prosthesis use may require different compensatory strategies at the trunk (Hebert and Lewicke, 2012) and shoulder (Carey et al., 2009) in comparison to myoelectric prosthesis use. Compensations by prosthesis users, irrespective of technology type, may put an increased load on the trunk and shoulder, increasing the risk of sustaining an overuse injury (Gambrell, 2008; Ostlie et al., 2011a). Compensatory movements have also been linked to discontinued use of prosthetic devices (Silcox et al., 1993). It is therefore important to understand the body compensations that are required for body-powered users, especially since they encompass a large number of current prosthesis users.

Some clinical performance-based outcome measures include ratings of body compensations as part of the evaluation of skill level of a prosthesis user (Wang et al., 2018; Resnik et al., 2017); however, movement quality is rated subjectively, and the assessment does not quantitatively record discrete movement patterns required by prosthesis users to complete a task (Cowley et al., 2016). Kinematic assessments using motion capture technologies have proven to be valuable for identifying movement strategies in non-disabled populations (Valevicius et al., 2018b) and in prosthesis user populations (Carey et al., 2008; Hebert and Lewicke, 2012). End-point kinematic measures such as reach time, grip aperture, and hand velocity have been shown, at least for myoelectric prosthesis users, to correlate to the results from the Southampton Hand Assessment Procedure (SHAP) (Bouwsema et al., 2012). However, the relationship between skill level and angular joint parameters such as RoM has not been established for prosthesis users of any technology. This information could be critical for improving rehabilitation outcomes by identifying key kinematic parameters to improve in order to increase skill level or reduce long term complications related to compensations.

In light of the above, the objective of the current study was to identify compensatory movement strategies of body-powered prosthesis users by assessing their angular joint kinematics while performing two standardized functional tasks. A second objective was to investigate the relation between body compensations and a clinical assessment of skill, in this case the AM-ULA. The AM-ULA was selected as the clinical assessment tool as it was developed specifically for an adult prosthesis user population with any level of amputation and using any type of prosthetic device (Resnik et al., 2013a). We hypothesized that body-powered prosthesis users would exhibit increased RoM at trunk DoFs and reduced RoM at shoulder DoFs due to the nature of the harness and cable system required to operate a body-powered prosthesis. In addition, we hypothesized that individuals who scored higher on the AM-ULA, indicating higher skill level, would display smaller

RoM values at trunk DoFs and greater RoM values at shoulder DoFs, therefore displaying RoM closer to normative values.

6.3 Methods

6.3.1 Participants

Five transradial prosthesis users were recruited to participate in the study (5 males; age: 50.8±13.0 years; height: 173.6±6.1 cm; weight: 87.6±14.9 kg; mean±SD). Four participants had an amputation of their right arm and one participant of their left arm. All prosthesis users used a body-powered prosthesis with a voluntary opening hook terminal device. Participant characteristics can be found in Table 6-1. The participants gave written informed consent to the experimental procedures, which were 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 6-1 Transradial prosthesis user characteristics. Successful trials indicate the number of trials completed by prosthesis user participants that did not contain errors and were used for data analysis. AM-ULA = Activities Measure for Upper Limb Amputees. N/A = Not Available.

	P1	**P2**	**P3**	**P4**	**P5**
Gender	Male	Male	Male	Male	Male
Age	59	55	45	64	31
Height (cm)	163	179	175	176	175
Amputation side	Right	Left	Right	Right	Right
Hand dominance prior to amputation	Right	Left	Right	Right	Right
Time since amputation (months)	336	310	115	141	62
Length of residual limb (cm)	16	12	11.5	N/A	13
AM-ULA score	47	39	36	32	30
Successful trials					
Cup Transfer task	9	7	9	7	10
Pasta Box task	9	10	9	8	10

6.3.2 Experimental Setup and Procedures

A 12-camera motion capture system (Bonita, Vicon Motion Systems Ltd, Oxford, UK), with a system accuracy of 0.5 mm was used to collect 3D marker trajectories at 120 Hz. 3D printed rigid plates containing three or four 11.1 mm reflective markers were attached to the pelvis, trunk, upper arms, forearms, hand, and terminal device (Figure 6-1). Marker plates were attached using hypo-allergenic, double-sided tape. A specific calibration pose was recorded for two seconds prior to data collection and used in the subsequent joint angle calculations as per Boser et al. (Boser et al., 2018).

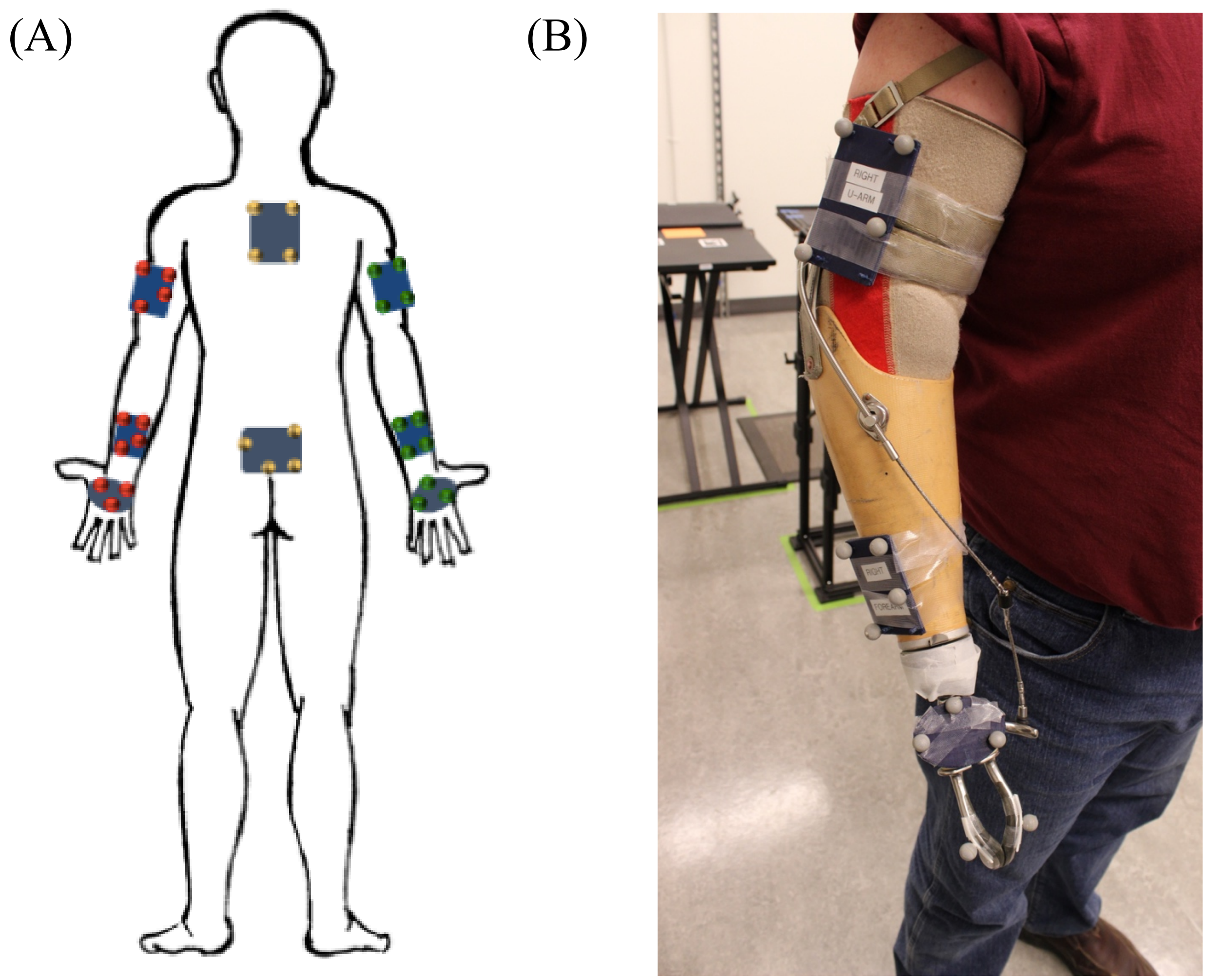

Figure 6-1 Placement of cluster model marker plates. The trunk plate is placed in between the two scapulae on the thoracic spine. The pelvis plate is placed at the mid-level of the posterior superior iliac spines (PSIS). Upper arm plates are placed in the middle of the upper arm. Forearm plates are placed on the distal dorsal side of the forearm, just above the radial and ulnar styloid. The hand plates are placed on the dorsal side of the hand. An analogous placement is attempted on prosthesis users. The schematic presentation of the marker plate placement is presented in (A). An example of the placement of marker plates for prosthesis users is presented in (B). The upper arm and forearm plates are placed in locations where the cables allow, and the hand plate is placed at the base of the terminal hook device.

Two standardized functional tasks, the Cup Transfer and Pasta Box tasks, were performed by the participants (Figure 4-1) as described in Valevicius et al. (Valevicius et al., 2018a). All participants completed the tasks with their prosthetic device. The Cup Transfer task included four movements, and required participants move two small compliant cups filled with beads to target locations in a box at table-top height with a middle partition. The first two movements had participants move the cups from the side of the box closest to the tested arm (the prosthetic side) to the other side of the box, and the last two movements had the participants move the cups back to the starting locations. After movements 2 and 4, participants returned their terminal device to a 'Home' position. The Pasta Box task had participants move a box of pasta from a side table to two shelves of different heights in front of them. The Pasta Box task included three movements, and the participants returned their terminal device to the 'Home' position after each movement. Participants practiced both tasks prior to data collection until they felt comfortable with the tasks. Participants completed 10 trials for each task, and the trials without errors were used for analysis. The AM-ULA was administered by a trained occupational therapist.

The AM-ULA was administered by a trained occupational therapist. The AM-ULA requires that the participant complete 18 tasks emphasizing household and self-care activities such as tying shoes, putting on a t-shirt, zipping a jacket, using scissors, and using a fork and spoon. The occupational therapist evaluates the prosthesis user based on task completion, speed, movement quality, the extent to which they use their prosthesis, and independence (Resnik et al., 2013a). Assessment of reliability for the AM-ULA displayed good results, with an ICC coefficient for test-retest reliability of .88 to .91 and ICC coefficient for interrater reliability of .84 to .85. Convergent validity was assessed by comparing to other tests of dexterity, and correlations ranged from .42 to .69, indicating moderate, but statistically significant correlations (Resnik et al., 2013a).

6.3.3 Experimental Data Analysis

Marker data were filtered using a fourth order, low-pass Butterworth filter with a cut-off frequency of 6 Hz (Winter, 2009). Filtered marker data were used to calculate three-dimensional joint kinematics. A global coordinate system was affixed to the task setup and local coordinate systems affixed to the marker plates, with the X-axis directed to the right, the Y-axis directed anteriorly, and the Z-axis directed superiorly. The Cardan angle rotation sequence X-Y-Z was used to calculate joint angles to obtain flexion/extension, lateral bending or abduction/adduction, and axial rotation (Boser et al., 2018). The orientations of the local coordinate systems during the calibration pose relative to the global coordinate system were used to calculate calibration transformation matrices. The transformation matrices were applied to the local coordinate systems during the functional tasks to virtually align them with the body (Boser et al., 2018). Eight DoFs were included in the analysis: trunk flexion/extension, lateral bending, and axial rotation; shoulder flexion/extension, abduction/adduction, and internal/external rotation; elbow flexion/extension; and forearm pronation/supination. Wrist motions were not included as all prosthesis users had fixed wrists. Trial data were segmented based on the movement of the testing arm as described in Valevicius et al., 2018, to create the discrete four or three movements that make up the Cup Transfer and Pasta Box tasks, respectively (Valevicius et al., 2018a). RoM values were extracted from the angular joint trajectories for each movement within a trial.

6.3.4 Statistical Analysis

The RoM values for prosthesis users were compared to a previously collected normative data set (9 females and 11 males; 18 right-handed and 2 left-handed; age: 25.8±7.2 years; height: 173.8±8.3 cm; mean±SD) (Valevicius et al., 2019). Statistical analysis was completed using the SPSS software (IBM Corporation, Armonk, NY, USA). For each task, a mixed-model ANOVA was conducted to test between-group differences across movements for RoM for all eight DoFs. The between-subject factor was the participant type (normative or prosthetic) and the within-subject factor was the movement (four movements for Cup Transfer Task; three movements for Pasta Box task). Significant main effects or interactions were reported if the Greenhouse-Geisser corrected P value was less than 0.05. Significant interactions ($P < 0.05$) were examined by conducting one-way repeated-measures ANOVAs for participant type on RoM for each movement. For measures that violated the homogeneity of variance assumption, tested with the Levene test, group differences were tested with the Welch t test (Metzger et al., 2012). A Pearson's product-moment correlation was run to assess the relationship between the AM-ULA score and RoM for each DoF. Statistical significance of the Pearson's product-moment correlation was set at $P < 0.05$. A correlation coefficient in the range of 0.00–0.09, 0.10–0.39, 0.40–0.69, 0.70–0.89, and 0.90–1.00 indicated a negligible, weak, moderate, strong, and very strong correlation, respectively (Schober and Schwarte, 2018).

6.4 Results

Table 6-1 lists the AM-ULA scores for the participants, which ranged from 30 to 47 out of a maximum score of 72. For the two functional tasks, prosthesis users exhibited a longer movement duration and total time for task completion that exceeded the normative values by more than two SD (Table 6-2). The mean RoM values are presented in Table 6-3 for the Cup Transfer task, and in Table 6-4 for the Pasta Box task.

Table 6-2 Cup Transfer and Pasta Box task results for mean task durations of a normative group and five transradial prosthesis users. Normative data presented in bold report the group mean duration and between-participant standard deviation (SD). Non-bold rows report the mean duration and within-participant SD for each prosthesis user. Green numbers represent a duration value that is above two SD from the normative mean. Data are presented for movement 1 (Mvmt1), movement 2 (Mvmt 2), movement 3 (Mvmt 3), and movement 4 (Mvmt 4).

Task Duration (sec)					
Cup Transfer Task					
	Mean (SD)				
	Mvmt 1	*Mvmt 2*	*Mvmt 3*	*Mvmt 4*	***Task***
Norms	**2.14 (0.27)**	**2.22 (0.29)**	**2.55 (0.33)**	**1.98 (0.24)**	**10.53 (1.32)**
P1	3.91 (0.24)	3.50 (0.33)	3.89 (0.23)	3.82 (0.51)	17.88 (0.97)
P2	3.78 (0.51)	3.33 (0.28)	3.77 (0.07)	3.89 (0.35)	17.52 (1.09)
P3	4.37 (0.29)	3.72 (0.36)	4.17 (0.31)	4.62 (0.51)	20.05 (1.14)
P4	7.07 (0.62)	5.93 (0.73)	6.17 (0.51)	7.06 (0.63)	30.39 (1.00)
P5	5.44 (0.54)	5.92 (0.57)	5.30 (0.36)	5.31 (0.49)	24.86 (1.14)
Pasta Box Task					
	Mean (SD)				
	Mvmt 1	*Mvmt 2*	*Mvmt 3*	***Task***	
Norms	**2.29 (0.28)**	**2.12 (0.27)**	**2.48 (0.34)**	**8.75 (1.20)**	
P1	3.54 (0.92)	2.73 (0.23)	3.88 (0.84)	15.08 (2.01)	
P2	3.16 (0.30)	3.06 (0.24)	3.49 (0.35)	15.67 (0.85)	
P3	4.27 (0.84)	3.41 (0.23)	3.98 (0.31)	17.01 (0.75)	
P4	5.08 (0.71)	4.80 (0.67)	5.63 (0.60)	22.61 (1.19)	
P5	4.81 (0.59)	4.34 (0.36)	5.10 (0.36)	18.42 (1.09)	

Table 6-3 Cup Transfer task results for range of motion (RoM) of a normative group and five transradial prosthesis users. Norms and prosthetic rows in bold report the group mean RoM and between-participant standard deviation (SD). Non-bold rows report the RoM and within-participant SD for each prosthesis user. Green and red numbers represent a RoM value that is above or below two SD from the normative mean, respectively. RoM is presented for movement 1 (Mvmt1), movement 2 (Mvmt 2), movement 3 (Mvmt 3), and movement 4 (Mvmt 4). Mean prosthetic RoM showing a statistically significant difference from norms is identified via one asterisk (*) for P < 0.05, two asterisks (**) for P < 0.01, and three asterisks (***) for P < 0.001.

	Trunk Flexion/Extension (degrees)				Shoulder Flexion/Extension (degrees)			
	RoM (SD)				RoM (SD)			
	Mvmt 1	*Mvmt 2*	*Mvmt 3*	*Mvmt 4*	*Mvmt 1*	*Mvmt 2*	*Mvmt 3*	*Mvmt 4*
Norms	**3.0 (1.5)**	**9.1 (3.3)**	**9.6 (3.1)**	**4.7 (2.5)**	**62.7 (13.5)**	**30.9 (6.2)**	**73.6 (10.4)**	**29.6 (9.0)**
Prosthetic	**17.0 (3.4)*****	**14.0 (4.0)***	**15.7 (4.9)****	**13.8 (3.0)*****	**33.7 (7.9)*****	**16.2 (4.1)*****	**41.3 (11.4)*****	**17.6 (5.2)***
P1	12.2 (1.2)	14.0 (1.1)	12.3 (0.5)	9.5 (1.2)	42.2 (1.2)	19.1 (2.1)	59.5 (1.5)	24.2 (1.9)
P2	17.0 (2.4)	10.5 (1.6)	9.4 (2.5)	15.6 (1.9)	36.1 (6.3)	11.4 (2.0)	40.8 (6.3)	16.7 (2.4)
P3	16.0 (2.5)	10.8 (0.9)	16.0 (1.0)	11.9 (1.1)	31.9 (2.9)	14.0 (1.3)	38.0 (2.7)	14.1 (1.2)
P4	18.1 (1.6)	14.1 (2.2)	19.9 (0.8)	15.8 (1.3)	37.1 (3.0)	21.6 (2.9)	40.5 (2.2)	21.4 (2.6)
P5	21.7 (2.1)	20.5 (2.7)	21.0 (1.8)	16.3 (2.0)	21.3 (1.9)	14.7 (2.2)	27.9 (2.0)	11.5 (1.1)
	Trunk Lateral Bending (degrees)				Shoulder Abduction/Adduction (degrees)			
	RoM (SD)				RoM (SD)			
	Mvmt 1	*Mvmt 2*	*Mvmt 3*	*Mvmt 4*	*Mvmt 1*	*Mvmt 2*	*Mvmt 3*	*Mvmt 4*
Norms	**4.8 (1.9)**	**7.2 (2.4)**	**6.2 (1.9)**	**4.0 (1.4)**	**27.5 (7.1)**	**18.7 (5.6)**	**28.7 (8.6)**	**26.1 (6.0)**
Prosthetic	**15.9 (5.4)****	**14.5 (5.7)*****	**15.6 (7.9)**	**16.6 (6.3)***	**25.2 (7.5)**	**22.6 (3.0)**	**24.1 (3.5)**	**24.7 (3.3)**
P1	13.3 (1.7)	14.5 (1.4)	12.6 (1.6)	15.6 (1.9)	25.3 (2.3)	22.2 (1.8)	26.6 (4.2)	22.9 (1.4)
P2	8.5 (2.6)	8.8 (1.1)	10.6 (2.0)	10.1 (2.0)	34.8 (4.5)	23.6 (3.6)	29.6 (4.1)	25.1 (4.5)
P3	17.9 (1.7)	15.2 (2.0)	13.1 (3.3)	26.7 (3.4)	21.7 (2.9)	24.0 (2.2)	18.3 (1.8)	24.0 (2.4)
P4	16.8 (2.1)	10.4 (1.8)	12.0 (1.7)	13.2 (1.6)	29.2 (4.7)	25.4 (2.4)	25.4 (5.7)	21.5 (2.4)
P5	22.8 (9.0)	23.5 (4.3)	29.7 (1.4)	17.1 (3.9)	15.1 (4.4)	17.5 (3.2)	23.3 (1.7)	30.2 (4.1)

	Trunk Axial Rotation (degrees)				Shoulder Internal/External Rotation (degrees)			
	RoM (SD)				RoM (SD)			
	Mvmt 1	*Mvmt 2*	*Mvmt 3*	*Mvmt 4*	*Mvmt 1*	*Mvmt 2*	*Mvmt 3*	*Mvmt 4*
Norms	**9.3 (2.5)**	**10.7 (2.8)**	**16.7 (4.2)**	**7.9 (2.4)**	**51.5 (13.9)**	**33.1 (7.5)**	**49.9 (12.2)**	**39.5 (9.6)**
Prosthetic	**17.5 (6.1)***	**15.2 (3.7)****	**23.4 (7.8)**	**15.1 (4.0)*****	**34.1 (7.1)***	**24.8 (6.9)***	**25.7 (9.6)*****	**27.8 (6.6)***
P1	23.9 (2.4)	21.7 (1.9)	33.9 (2.5)	18.6 (2.4)	45.7 (2.0)	34.1 (4.1)	38.6 (2.0)	25.7 (3.8)
P2	7.9 (2.1)	13.8 (3.6)	14.5 (1.8)	8.8 (1.6)	29.4 (7.6)	26.2 (7.5)	23.7 (3.9)	29.5 (5.7)
P3	17.9 (2.8)	12.6 (1.6)	28.3 (3.3)	13.6 (1.6)	27.7 (3.6)	22.3 (2.4)	16.5 (5.0)	28.4 (1.9)
P4	21.1 (1.5)	14.5 (2.5)	22.5 (6.7)	16.7 (1.5)	35.2 (4.9)	26.1 (4.8)	17.5 (4.8)	37.0 (1.8)
P5	16.6 (3.5)	13.5 (3.5)	18.0 (2.9)	17.6 (2.5)	32.7 (4.3)	15.1 (2.1)	32.3 (3.2)	18.7 (1.5)
	Elbow Flexion/Extension (degrees)				Forearm Pronation/Supination (degrees)			
	RoM (SD)				RoM (SD)			
	Mvmt 1	*Mvmt 2*	*Mvmt 3*	*Mvmt 4*	*Mvmt 1*	*Mvmt 2*	*Mvmt 3*	*Mvmt 4*
Norms	**44.6 (9.4)**	**60.4 (8.1)**	**84.6 (9.3)**	**48.3 (6.0)**	**31.0 (11.5)**	**46.9 (12.6)**	**64.2 (11.2)**	**46.6 (9.7)**
Prosthetic	**23.8 (17.8)****	**16.7 (7.2)*****	**28.4 (18.1)*****	**22.3 (10.1)*****	**12.4 (2.0)****	**10.2 (1.7)*****	**15.5 (6.2)*****	**13.0 (4.8)*****
P1	55.1 (2.9)	23.9 (2.4)	60.3 (3.0)	38.3 (2.2)	13.9 (1.6)	13.0 (2.1)	24.4 (2.2)	19.0 (2.4)
P2	21.2 (2.6)	14.4 (0.9)	25.9 (3.6)	22.3 (1.9)	10.9 (2.0)	9.2 (1.5)	9.2 (1.7)	10.0 (2.2)
P3	13.3 (3.3)	5.8 (0.7)	18.9 (4.7)	15.4 (2.4)	11.5 (2.6)	8.7 (1.4)	18.5 (3.1)	16.6 (2.9)
P4	15.7 (3.3)	22.4 (2.4)	16.6 (1.5)	12.3 (3.8)	10.6 (1.6)	10.5 (2.1)	10.6 (1.1)	7.0 (1.8)
P5	13.8 (3.5)	17.1 (4.3)	20.5 (2.4)	23.3 (2.2)	15.2 (2.3)	9.6 (2.6)	14.6 (1.5)	12.6 (1.8)

Table 6-4 Pasta Box task results for range of motion (RoM) of a normative group and five transradial prosthesis users. Norms and prosthetic rows in bold report the group mean RoM and between-participant standard deviation (SD). Non-bold rows report the RoM and within-participant SD for each prosthesis user. Green and red numbers represent a RoM value that is above or below two SD from the normative mean, respectively. RoM is presented for movement 1 (Mvmt1), movement 2 (Mvmt 2), and movement 3 (Mvmt 3). Mean prosthetic RoM showing a statistically significant difference from norms is identified via one asterisk (*) for P < 0.05, two asterisks (**) for P < 0.01, and three asterisks (***) for P < 0.001.

	Trunk Flexion/Extension (degrees)			Shoulder Flexion/Extension (degrees)		
	RoM (SD)			RoM (SD)		
	Mvmt 1	*Mvmt 2*	*Mvmt 3*	*Mvmt 1*	*Mvmt 2*	*Mvmt 3*
Norms	**4.9 (1.6)**	**3.6 (1.0)**	**4.9 (1.4)**	**69.3 (7.6)**	**72.1 (9.7)**	**86.0 (9.9)**
Prosthetic	**26.5 (11.6)***	**14.8 (2.7)****	**28.0 (9.7)****	**41.7 (9.5)*****	**47.9 (14.6)*****	**52.8 (15.3)*****
P1	12.2 (2.1)	11.5 (1.2)	20.7 (2.6)	56.8 (2.9)	70.6 (2.2)	70.0 (3.9)
P2	37.9 (10.1)	17.3 (6.2)	33.7 (5.0)	44.3 (9.4)	54.5 (4.0)	66.5 (6.3)
P3	39.2 (2.4)	17.6 (1.9)	42.4 (2.5)	38.6 (1.9)	38.8 (1.6)	50.8 (2.0)
P4	22.5 (2.1)	14.8 (1.4)	21.6 (2.1)	36.5 (3.9)	39.3 (1.5)	41.9 (1.9)
P5	20.8 (4.6)	12.6 (2.5)	21.7 (2.8)	32.2 (3.1)	36.2 (2.9)	34.6 (2.5)
	Trunk Lateral Bending (degrees)			Shoulder Abduction/Adduction (degrees)		
	RoM (SD)			RoM (SD)		
	Mvmt 1	*Mvmt 2*	*Mvmt 3*	*Mvmt 1*	*Mvmt 2*	*Mvmt 3*
Norms	**8.7 (2.8)**	**5.6 (2.0)**	**11.8 (2.8)**	**19.3 (6.5)**	**25.6 (8.8)**	**28.9 (9.1)**
Prosthetic	**19.1 (11.1)**	**12.7 (4.4)***	**23.3 (6.8)***	**29.8 (10.3)***	**26.3 (8.3)**	**39.4 (10.2)***
P1	6.9 (2.0)	8.2 (1.4)	14.5 (2.3)	29.5 (4.1)	18.5 (2.1)	27.2 (3.2)
P2	20.6 (3.3)	12.1 (2.0)	27.0 (4.3)	43.0 (4.5)	37.5 (5.3)	48.3 (5.9)
P3	23.5 (1.9)	18.7 (1.9)	26.2 (1.3)	36.7 (2.8)	28.8 (3.3)	43.9 (3.0)
P4	9.9 (0.8)	9.1 (0.6)	18.1 (2.5)	21.6 (1.3)	29.1 (1.8)	29.7 (2.9)
P5	34.5 (3.3)	15.5 (2.8)	30.9 (2.4)	18.2 (2.4)	17.7 (3.9)	48.1 (2.7)

	Trunk Axial Rotation (degrees)			Shoulder Internal/External Rotation (degrees)		
	RoM (SD)			RoM (SD)		
	Mvmt 1	*Mvmt 2*	*Mvmt 3*	*Mvmt 1*	*Mvmt 2*	*Mvmt 3*
Norms	**17.8 (2.4)**	**15.1 (3.0)**	**25.5 (3.0)**	**44.0 (7.9)**	**32.6 (6.7)**	**54.2 (6.8)**
Prosthetic	**27.7 (5.4)*****	**24.5 (7.9)**	**30.0 (6.6)**	**44.6 (16.8)**	**41.5 (12.4)***	**48.1 (10.3)**
P1	36.3 (3.7)	34.4 (1.8)	40.4 (2.5)	36.8 (4.4)	37.6 (3.8)	44.2 (6.3)
P2	27.5 (3.6)	25.7 (2.2)	31.8 (5.3)	73.4 (4.8)	60.8 (4.3)	58.0 (4.4)
P3	22.3 (1.4)	29.0 (3.0)	27.8 (3.6)	35.8 (2.9)	34.6 (3.0)	41.7 (5.1)
P4	24.2 (1.4)	14.3 (2.0)	26.8 (2.1)	45.2 (2.8)	45.7 (1.2)	60.0 (3.5)
P5	28.0 (2.8)	19.3 (2.5)	23.2 (3.3)	31.9 (4.1)	28.9 (4.3)	36.7 (3.3)
	Elbow Flexion/Extension (degrees)			**Forearm Pronation/Supination (degrees)**		
	RoM (SD)			RoM (SD)		
	Mvmt 1	*Mvmt 2*	*Mvmt 3*	*Mvmt 1*	*Mvmt 2*	*Mvmt 3*
Norms	**76.4 (10.6)**	**81.2 (9.6)**	**88.4 (11.6)**	**77.0 (15.9)**	**51.4 (18.2)**	**90.9 (17.3)**
Prosthetic	**39.2 (20.4)*****	**42.3 (17.4)*****	**47.3 (22.1)*****	**20.0 (8.8)*****	**18.9 (7.0)****	**18.0 (5.0)*****
P1	72.8 (6.5)	71.2 (2.5)	77.6 (4.2)	32.9 (3.1)	23.1 (1.8)	25.0 (0.9)
P2	41.6 (1.4)	39.4 (3.3)	46.4 (2.0)	12.8 (1.3)	9.7 (0.8)	11.6 (3.1)
P3	28.3 (3.8)	36.0 (2.0)	25.0 (3.0)	25.3 (1.7)	27.4 (1.4)	19.1 (2.2)
P4	33.3 (3.5)	40.9 (2.6)	59.7 (4.9)	14.4 (1.9)	19.8 (1.1)	15.5 (1.2)
P5	20.1 (3.4)	24.2 (1.6)	27.6 (4.4)	14.7 (7.1)	14.4 (6.8)	18.9 (8.7)

6.4.1 Angular Joint Kinematics

Trunk, shoulder, and elbow DoF RoM values for prosthesis users in comparison to normative values are presented in Figure 6-2 for the Cup Transfer task and Figure 6-3 for the Pasta Box task. Compared to normative values, average values for prosthesis users displayed a statistically significant increase in RoM at most trunk DoFs for both tasks. Prosthesis users displayed a statistically significant decrease in RoM for shoulder flexion/extension across all movements for both tasks compared to normative values. Shoulder abduction/adduction showed no statistically significant RoM difference between prosthesis and normative values for the Cup Transfer task. However, there was a statistically significant increase in shoulder abduction/adduction RoM for prosthesis users in movements 1 and 3 of the Pasta Box Task, with an average RoM difference of 11 degrees. Shoulder internal/external rotation RoM was significantly reduced for prosthesis users for all movements of the Cup Transfer task, with differences ranging from 8 to 24 degrees. For the Pasta Box task, there was a statistically significant increase in shoulder internal/external rotation RoM for movement 2 in prosthesis users, however this may have been affected by a single outlier (Figure 6-3). Elbow flexion/extension and forearm pronation/supination RoM showed a statistically significant reduction for prosthesis users across all movements for both tasks.

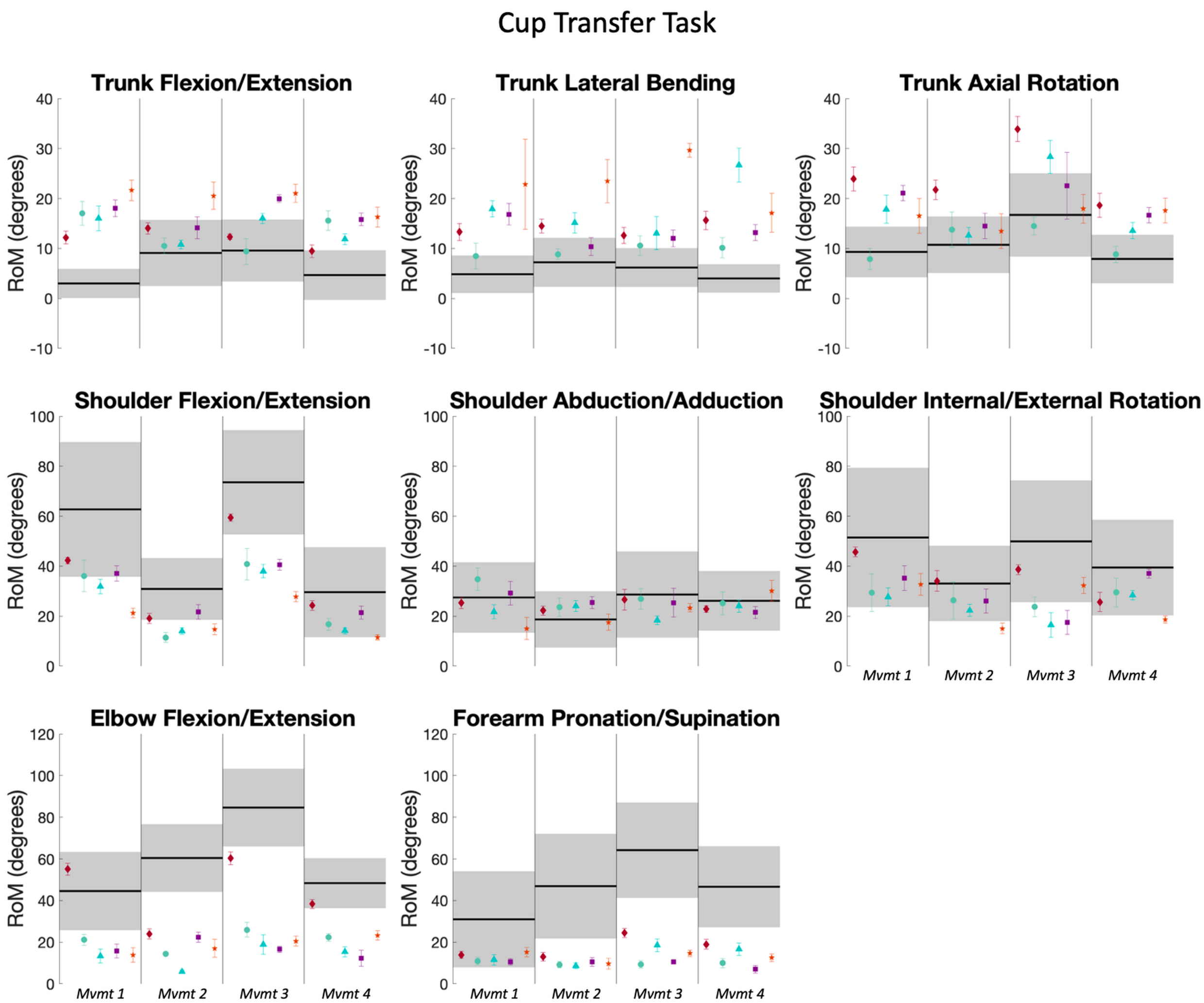

Figure 6-2 Cup Transfer task RoM results for the five transradial body-powered prosthesis users presented for eight DoFs (trunk flexion/extension, lateral bending, axial rotation; shoulder flexion/extension, abduction/adduction, internal/external rotation; elbow flexion/extension, forearm pronation/supination). Mean normative RoM and two between-participant standard deviations are indicated by the black horizontal line and the grey shading, respectively. Prosthesis user participants are plotted as individual markers with within-participant standard deviations as error bars. Prosthesis user participants are plotted left to right in order of best to worst AM-ULA scores. Each DoF graph is divided into four sections, each representing movement 1 (*Mvmt1*), movement 2 (*Mvmt 2*), movement 3 (*Mvmt 3*), and movement 4 (*Mvmt 4*).

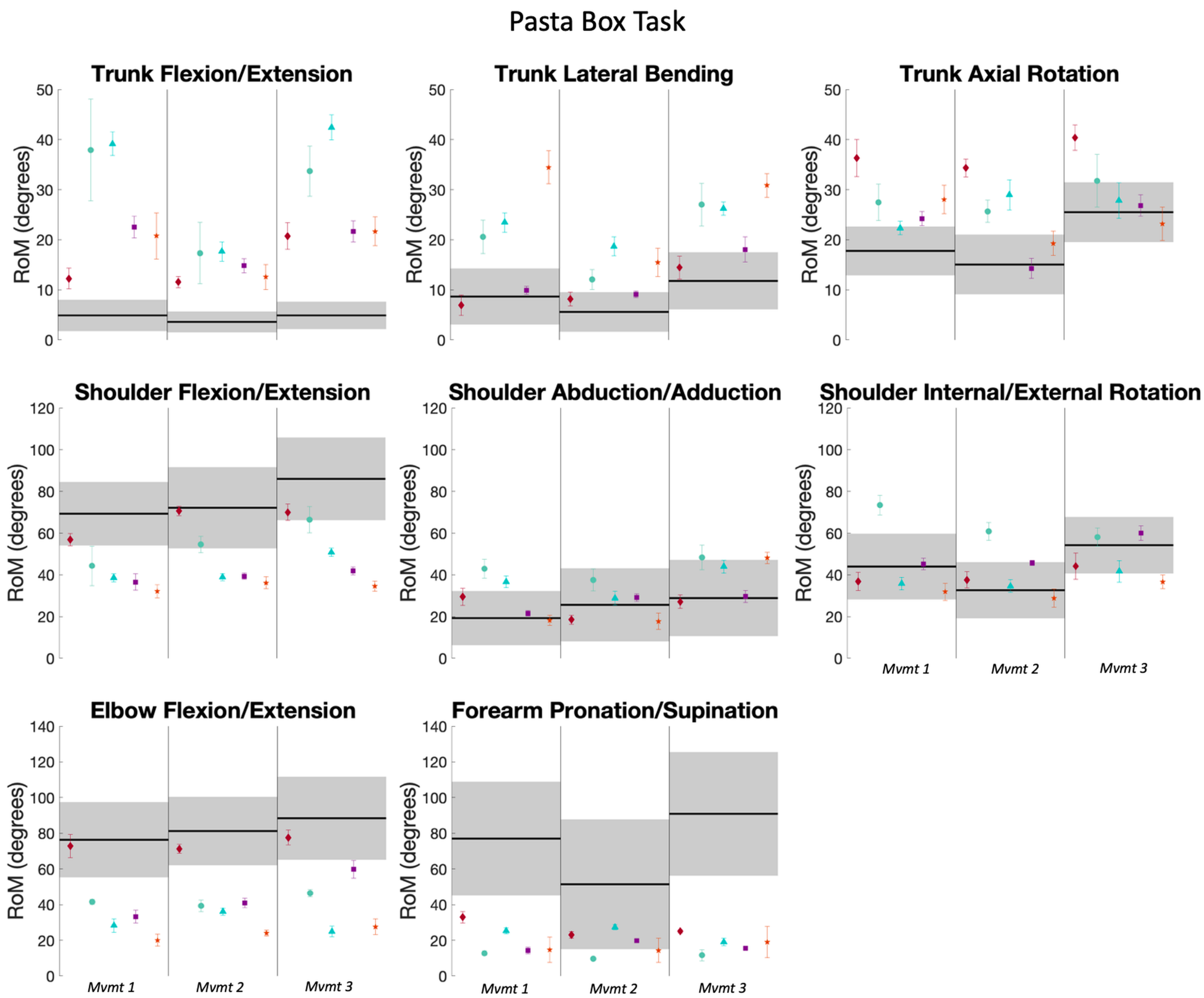

Figure 6-3 Pasta Box task RoM results for the five transradial body-powered prosthesis users presented for eight DoFs (trunk flexion/extension, lateral bending, axial rotation; shoulder flexion/extension, abduction/adduction, internal/external rotation; elbow flexion/extension, forearm pronation/supination). Mean normative RoM and two between-participant standard deviations are indicated by the black horizontal line and the grey shading, respectively. Prosthesis user participants are plotted as individual markers with within-participant standard deviations as error bars. Prosthesis user participants are plotted left to right in order of best to worst AM-ULA scores. Each DoF graph is divided into three sections, each representing movement 1 (*Mvmt1*), movement 2 (*Mvmt 2*), and movement 3 (*Mvmt 3*).

6.4.2 AM-ULA Correlations

Pearson's product-moment correlation coefficient results are presented in Table 6-5 and in Appendix D, Figures D.1 to D.6, for both tasks. For the Cup Transfer task, AM-ULA scores displayed a strong negative correlation with trunk flexion/extension RoM for movements 1, 2, and

4, indicating that, with increased skill, trunk flexion/extension RoM decreased. Trunk axial rotation for movements 2 and 3 was positively correlated with AM-ULA scores, with greater rotation observed with higher AM-ULA scores. Shoulder flexion/extension RoM was positively correlated with AM-ULA scores for movements 1 and 3. Elbow flexion/extension RoM was strongly positively correlated with AM-ULA score for three of the four movements, indicating increased elbow flexion/extension RoM with higher AM-ULA score.

Table 6-5 Pearson's product-moment correlation coefficient results for range of motion and AM-ULA scores for the group of five prosthesis users. Two asterisks (**) indicate a correlation that is significant at the 0.01 level, and one asterisk (*) indicates a correlation that is significant at the 0.05 level. A correlation coefficient in the range of 0.00–0.09, 0.10–0.39, 0.40–0.69, 0.70–0.89, and 0.90–1.00 indicate a negligible, weak, moderate, strong, and very strong correlation, respectively (Schober and Schwarte, 2018)**.**

		Cup Transfer task				**Pasta Box task**		
		Mvmt 1	*Mvmt 2*	*Mvmt 3*	*Mvmt 4*	*Mvmt 1*	*Mvmt 2*	*Mvmt 3*
Trunk	Flexion/Extension	–0.927*	–0.462	–0.794	–0.815	–0.232	–0.200	0.001
	Lateral Bending	–0.670	–0.355	–0.557	–0.116	–0.624	–0.460	–0.608
	Axial Rotation	0.204	0.815	0.597	–0.013	0.739	0.870	0.987**
Shoulder	Flexion/Extension	0.771	0.042	0.922*	0.660	0.990**	0.959**	0.936*
	Abduction/Adduction	0.373	0.226	0.374	–0.438	0.503	–0.057	–0.442
	Internal/External Rotation	0.618	0.867	0.504	–0.003	0.166	0.224	0.027
Elbow	Flexion/Extension	0.902*	0.246	0.902*	0.784	0.947*	0.909*	0.674
Forearm	Pronation/Supination	0.038	0.657	0.631	0.639	0.745	0.225	0.469

For the Pasta Box task, AM-ULA scores displayed strong positive correlations with trunk axial rotation, shoulder flexion/extension, and elbow flexion/extension. Trunk axial rotation RoM displayed a strong positive correlation with AM-ULA scores for all three movements. Shoulder flexion/extension RoM also displayed a strong positive correlation with AM-ULA scores, where participants who scored higher on the AM-ULA displayed an increased shoulder flexion/extension RoM that was closer to the norm; all four movements displayed a Pearson's correlation coefficient value above 0.90. A larger elbow flexion/extension RoM was observed with a higher AM-ULA score.

6.5 Discussion

Compensatory strategies have been linked to potential overuse injuries and prosthetic device rejection (Gambrell, 2008; Ostlie et al., 2011a; Silcox et al., 1993). The movement strategies used by body-powered prosthesis users are underrepresented in the literature compared to users of newer technologies such as myoelectric prostheses, despite their prevalence in their clinical use. Identifying movement strategies in this population could help reduce long term-risks by informing approaches to intervention. Our findings indicate that body-powered transradial prosthesis users compensate primarily with the trunk and exhibit mostly restricted shoulder flexion/extension RoM, near normal shoulder abduction/adduction RoM and significantly impaired elbow motion, which is consistent with our first hypothesis.

6.5.1 Compensatory Movements

The increased trunk movement as a main compensatory feature in body-powered prosthesis users is in line with previous kinematic studies of both upper limb body-powered and myoelectric prosthesis users (Carey et al., 2008; Hebert and Lewicke, 2012; Hussaini et al., 2017; Major et al., 2014; Metzger et al., 2012). Increased reliance on trunk flexion/extension or lateral bending was task dependent. Prosthesis users in the current study displayed more trunk lateral bend compensation in the Cup Transfer task, whereas they compensated for the Pasta Box task with trunk flexion/extension, displaying on average a 19 degree larger RoM than norms. Similar to these results, Major et al. showed an increased reliance on trunk lateral bending for a carton pouring task and increased reliance on trunk flexion/extension for a tray transfer task, the latter requiring a cross-body movement as does the Pasta Box task (Major et al., 2014). In the present study, reaching for the box of pasta on the side table challenged trunk flexion/extension the most. The side table was lower than the cart and the difficulty for prosthesis users to reach for objects that are in their periphery and at a lower placement was evidenced by the increased trunk flexion required to successfully complete this portion of the task.

In our sample of body-powered prosthesis users, shoulder movement was restricted compared to normative motion, indicating impairment (loss of motion). Shoulder flexion/extension was significantly reduced for both tasks, with an average reduction of 22 and 28 degrees compared to normative values for the Cup Transfer and Pasta Box tasks, respectively. This restriction is most likely due to the harnessing and control cable requirement of a body powered prosthesis. Shoulder movements are required to create tension on the Bowden cable system that allows the terminal device to open and close (Bertos and Papadopoulos, 2018). When transporting an object, the user must be careful to not move the shoulder or scapula in a way such that tension is put on the cable, inadvertently opening the grip and dropping the object. Hence, intentionally restricting shoulder motion may be a means to reduce this risk. Shoulder abduction/adduction was not significantly different from normative values for all movements of the Cup Transfer task. However, prosthesis users increased their reliance on shoulder abduction/adduction for movements 1 and 3 of the Pasta Box task, when reaching for the box of pasta in their periphery. The findings from the Cup Transfer task contrasts other studies on myoelectric prosthesis users that found increased shoulder abduction/adduction to complete tasks such as cutting, page turning, and carton lifting (Major et al., 2014). These differences may stem from the different technology used (myoelectric versus body-powered), or the different task demands. Due to the limited availability of results in the literature regarding shoulder abduction/adduction movements in prosthesis users, it is critical to further research this specific movement in populations using both myoelectric and body-powered prostheses, performing the same tasks.

Other factors that were not measured may have influenced movement strategies of prosthesis users in this study. Foot placement was not standardized in this study. Although participants were instructed to stand on a mat and not walk around the testing set up, they were free to shift their weight and alter foot placement to accomplish the task. Foot movement was not recorded, and could have altered the magnitude of compensations observed, as previous research has shown that foot placement during reaching tasks does alter movement patterns (Gillette and Abbas, 2003). Finally, prosthetic arm length was not measured, as each prosthesis had been optimally fit by the prosthetist and was not modifiable. A longer prosthetic limb could affect movement by potentially reducing compensations observed at the trunk when reaching for objects further away. The effect of prosthetic device length on movement mechanics is not well understood and should be investigated in future studies.

6.5.2 Clinical Assessment Correlation

A second focus of this study was a comparison of RoM outcomes with AM-ULA results as a proxy for skill level. Higher skilled users tended to use trunk axial rotation as a compensation more than trunk lateral bending or trunk flexion, which were strategies employed by less skilled users. This increase in RoM for trunk axial rotation was in contrast to our second hypothesis, where we hypothesized that more skilled users would display lesser amounts of compensation at the trunk. For the Pasta Box task specifically, higher AM-ULA scores were associated with an increased reliance on trunk axial rotation to reach for the box of pasta at the side table, instead of turning, facing the side table and using more trunk flexion/extension as less skilled users did. Being able to highlight this difference in skill based on task requirements reinforces that more functional tasks (Taylor et al., 2018) requiring movement outside of the zone in front of the body (Wang et al., 2018) should be used in prosthesis user evaluation settings.

Consistent across both tasks, a higher level of skill was associated with more normal shoulder flexion/extension movements. These findings indicate that less skilled users may intentionally restrict shoulder motion as they are less confident with the harnessing and/or the ability to place the prosthesis in space without affecting the cable tension and operation of the terminal device. Hence, they move “en bloc”, with trunk flexion as the major compensation and the shoulder kept at their side. With greater skill, users take advantage of greater freedom of movement of the shoulder and axial rotation of the trunk to position the prosthesis. More normal values for shoulder flexion/extension may in turn reduce compensation at other DoFs in the upper body kinematic chain.

There was also a strong correlation of skill level with elbow flexion/extension RoM for five of the seven movements across the two tasks. It might be expected to see reduction in elbow motion for prosthesis users, as most transradial socket designs will interfere with elbow flexion and certainly forearm pronation/supination. Interestingly, the prosthesis user with the best skill level had elbow flexion/extension RoM within normative values for two of the four Cup Transfer task movements and for all movements of the Pasta Box task. This participant also had the longest residual limb and was tested the longest time since amputation. The improved elbow motion afforded by a longer residual limb may have directly contributed to his ability to more effectively perform the tasks.

The association between better clinical scores and specific kinematic parameters is consistent with previous literature. Bouwsema et al. found that myoelectric prosthesis users who scored higher on the SHAP displayed hand kinematic movement patterns, namely shorter movement times and grasp aperture plateau times, that were closer to normative values (Bouwsema et al., 2012). However, they did not report any association with angular joint kinematics, reporting that most participants had similar movement patterns for their tasks. The higher functional demands of our tasks may have allowed better distinguishing of movement patterns across skill level of the participants. In future work, quantifying the modifiability of these joint movement compensations and skill improvements with training (Dromerick et al., 2008; Huinink et al., 2016b) will be important for assessing the responsiveness of the kinematic measures.

Although our study identified clear trends in compensatory strategies of body-powered prosthesis users, the limited sample size makes it difficult to generalize the identified strategies to all body-powered prosthesis users. A greater sample size with a wider range of skill level, and assessing performance before and after training, would allow evaluation of the modifiability of the compensations observed. Furthermore, the tasks performed in this study should be used to directly compare differences between body-powered and myoelectric user compensatory strategies to further investigate differences attributed to the technology used. Notably, the normative data set used for comparison purposes in this study had a mean age half that of the prosthesis users. A younger population could display differences in movement strategies compared to an older population, and the use of age-matched cohorts for comparison may alter the magnitude of the compensations observed.

6.6 Conclusion

This study evaluated prosthesis users' movement strategies using an angular joint kinematic assessment during functional tasks and explored the association between RoM patterns and AM-ULA scores. Body-powered prosthesis users mainly compensated with trunk movement and showed reduced motion for shoulder flexion/extension, with relatively normal shoulder abduction/adduction motion. In addition, we have uniquely explored the relationship between angular kinematic strategies employed by transradial body-powered prosthesis users and their skill level. Our preliminary findings suggest that increased skill was associated with less trunk flexion, increased trunk axial rotation, and more normal (increased) shoulder and elbow flexion/extension range. These insights into the compensatory strategies of transradial body-powered prosthesis users and the relation to skill level should be further expanded to study the effects of training on the modifiability of the compensatory patterns observed.

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Chapter 7. Conclusions and Future Directions

7.1 Conclusions

Upper limb loss can have a severe effect on upper limb function and the ability to complete self-care activities and everyday tasks. Loss of distal hand dexterity will directly alter the movement patterns at more proximal joints of the upper body (Klein et al., 2011). In some cases, those altered movement patterns may be adaptive in ways that allow the prosthesis user to complete the task at hand in a more ergonomic and efficient manner (Major et al., 2014). However, in the case of compensatory strategies, they can lead to unwanted movement patterns that may increase the risk of overuse injuries, both on the impaired and sound limb (Gambrell, 2008). Compensatory strategies may also lead to rejection of prosthetic devices and discontinued use (Silcox et al., 1993). Recent advancements in prosthetic devices attempt to help individuals with upper limb loss to improve both form and function (Carlsen et al., 2014). Improvements in function can be achieved through designing activity-specific devices (Carlsen et al., 2014), integrating active wrist controllers into the devices (Cowley et al., 2016), or even integrating advanced neural implant technologies for individuals to experience sensory feedback (Marasco et al., 2015). Changes in prosthetic technologies, such as the addition of a mechanical wrist joint, can allow an individual to perform movements of daily living more naturally (Bertels et al., 2009). Therefore, it is important to understand how advancements in prosthetic devices directly impact functional movement, more specifically movement efficiency, movement quality, and angular joint strategies. Sensitive assessment tools are required to precisely quantify functional movement, and the clinical assessment tools currently available do not fill this gap (Resnik et al., 2017; Wang et al., 2018).

In this thesis, we developed a novel kinematic assessment, along with optical motion capture technology and two standardized functional tasks, to quantify upper body movement both for hand function and angular joint kinematics. The standardized functional tasks were designed with specific criteria in mind, which included being challenging enough for prosthesis users to complete, but that would be representative of 'real-world' activities they would need to complete in their daily life. They also needed to be composed of standardized movement sequences that ensured repeatable movement and could be collapsed across trials and participants to create a non-disabled data set for future comparison to populations with impairments. Following development, our novel kinematic assessment was validated in a non-disabled population and used to identify consistent and repeatable hand movement and angular joint movement. It was used in a transradial body-powered prosthesis user population to illustrate that it is sensitive to detecting compensatory strategies in impaired populations.

Prior to using this assessment to study prosthesis users, it was important to collect and analyze data in non-disabled participants to create a comprehensive benchmark dataset on hand function and angular kinematics. The tasks were segmented based on hand movement data into reach-grasp and transport-release segments, which also reflect the building blocks for specific object manipulation movements. An advantage of this segmentation is the ability to analyze various measures with a high level of precision. For example, hand function data is much more meaningful given a segmentation based on reach-grasp and transport-release segments, but this level of detail is typically not needed for angular joint movement measures such as RoM, where movement-based segmentation is sufficient.

Hand function data were first analyzed and included in the non-disabled data set, with a focus on hand trajectory, hand velocity, and grip aperture. All these aspects of hand function displayed small variability among the non-disabled cohort of participants. Specific task requirements, such as cross-body movements, lateral movements, overcoming barriers and obstacles, and various grasp patterns, were clearly identified in the hand function kinematic data. This indicates that our assessment is sensitive enough to pick up environmental task differences, which are then reflected in our measures. This level of sensitivity and detail is necessary when the goal is to detect how small adjustments or improvements to prostheses impact movement strategies.

Angular joint kinematics were next integrated into the comprehensive non-disabled dataset. Peak angle, RoM, and peak angular velocity were extracted from kinematic time series. Trunk, shoulder, elbow, and wrist joints were included in our analysis. A key difference in this study, typically not addressed in non-disabled studies investigating upper limb movement, is the inclusion of the trunk into the analysis. Although trunk movement was minimal for both tasks, it is important to include it in non-disabled population studies, especially as the goal is for that data to serve as a benchmark to compare against populations with impairments. Once again, key task characteristics displayed distinct movement strategies at upper body joints. This kinematic analysis was sensitive enough to small changes in hand position due to different grasp patterns. Some DoFs displayed increased variability compared to others, especially forearm pronation/supination. One reason causing the increased variability is participants selecting different movement strategies. Another reason may be the height difference among participants. The cart was set to a standard counter height, which would cause participants of different heights to display different endpoint trajectories and possibly different distal joint angles. Quantifying variability in non-disabled individuals enhances our understanding of the natural movement variability for a given task, especially one mimicking a 'real-world' environment. Later comparison of prosthesis users against the natural variability of non-disabled individuals can give a sense of whether prosthesis users fall within or outside the natural movement range of non-disabled individuals.

Finally, this thesis ends by applying our novel assessment tool to prosthesis users. We selected a cohort of transradial body-powered prosthesis users given that body-powered prostheses are commonly prescribed by clinicians (Huang et al., 2001) and their compensatory mechanisms are still not well understood. Our study showed that these users primarily compensate with the trunk, which was consistent with other prosthesis user studies (Carey et al., 2008; Hebert and Lewicke, 2012). Body-powered prosthesis users all displayed reduced shoulder flexion/extension, likely due to the harnessing system that is used to control the device. Another finding of this study was the preliminary exploration of the relationship between RoM results and AM-ULA scores, which indicated that there may be an association between skill level and compensatory movements for specific DoFs, namely trunk flexion/extension and shoulder flexion/extension. This was a novel finding that highlights a potential opportunity for rehabilitation interventions to improve skill level and thereby potentially reduce compensatory strategies.

7.2 Limitations

With respect to the studies involving non-disabled participants, some limitations include the sample of participants that was selected, the reliability analysis, and our selected marker set. The selected sample of participants included young healthy adults and the data was collapsed across sexes. Although young healthy adults would be representative of how the majority of a healthy non-disabled population would move, this sample may not be representative of how an older population would behave. Given that many motor impairments, such as stroke, may occur later in life, an age-matched non-disabled cohort should be used for comparison purposes to certain populations with impairments. Therefore, future work needs to be completed on expanding our non-disabled data set to different age groups, but also looking at differences between sexes. Moreover, our study only investigated between-session reliability, which is only one type of reliability. Reliability across multiple test administrators should also be investigated to complete the reliability analysis.

More specific to angular joint kinematics, caution must be taken when using specific measures, such as peak angle, given the marker set that we used. We used a previously established marker set by Boser et al., which only uses marker clusters. The simple marker set is easy to use, especially in a clinical environment, but does create some offsets at trunk flexion/extension, elbow, and wrist DoFs (Boser et al., 2018). RoM is not as affected to the same extent as peak angle values by this type of marker set, therefore may be a more valid outcome measure to use when assessing prosthesis user performance.

With respect to the prosthesis user study, the small sample size is a limitation for extrapolating any general trends to a greater prosthesis user population. A greater sample size of body-powered prosthesis users would give us a better understanding of compensatory strategies specific to this user group. In addition, the kinematic assessment developed in this thesis should be completed on myoelectric prosthesis users and prosthesis users with higher levels of amputation to understand differences in compensatory strategies across different devices and levels of amputation.

7.3 Future Directions

Moving forward, this kinematic assessment tool could be expanded to a wider prosthesis user population, including both body-powered and myoelectric prosthesis users, and other levels of amputation. Although a preliminary comparison was completed between the body-powered user cohort and the myoelectric literature, drawing any definitive conclusions on differences in compensatory strategies would be difficult given that different tasks were used in the literature. The wide range of tasks present in the literature, ranging from RoM tasks (Carey et al., 2009) to ADL tasks (Cowley et al., 2016; Mateo et al., 2015) currently make comparisons across different studies difficult. Comparing myoelectric prosthesis users for the same tasks as our body-powered users will allow us to gain detailed insight into how compensatory strategies may be different with different devices, across movement phases. In addition to investigating compensatory strategies present at upper body joints, it would be informative to compare end-effector trajectories to examine how prosthesis users manipulate their end-point kinematics to successfully complete the task.

The developed standardized protocol could be used in the future to assess responsiveness to change, particularly to track rehabilitation progress over time. Performing such an assessment prior to receiving a new device and then at a 6-month or 1-year follow up would give rich information to clinicians about the progress of their patient on how they are using their prosthetic device (Bouwsema et al., 2012). Given that our novel kinematic assessment displayed good between-session reliability in non-disabled individuals suggests that this assessment will be appropriate in tracking changes over time. However, sensitivity or responsiveness to change has yet to be assessed.

Furthermore, this kinematic assessment tool can be used to track the effectiveness of prosthetic technology advancements. Advancements in control strategies for multiple DoF prostheses, including pattern recognition (Powell and Thakor, 2013), multi-articulating hands (Jette, 2017), or wrist motion (Cowley et al., 2016), aim to restore more natural movement patterns in prosthesis users. Evaluating if these specific advancements do, in fact, benefit the user by reducing compensatory strategies can drive future prosthetic development.

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Appendix A

Table A.1 Tasks used in prosthesis user kinematic assessments. Tasks are separated into a variety of categories, including range of motion tasks, tasks mimicking activities of daily living, simple grasping and pointing tasks, feeding activities, self-care activities, house-hold activities, and a clinical task.

Type of Task	Task	Authors
Range of motion	Wrist flexion/extension	Abd Razak et al., 2013
	Wrist pronation/supination	Abd Razak et al., 2013
	Elbow flexion	Carey et al., 2009
Mimicking activities of daily living	Hand to contralateral ASIS	Bertels et al., 2009
	Hand to mouth	Bertels et al., 2009
	Hand to sternum	Bertels et al., 2009
	Hand to ipsilateral hip pocket	Bertels et al., 2009
	Hand to face level	Bertels et al., 2009
Simple grasping/pointing	Direct grasping task	Bouwsema et al., 2010
		Bouwsema et al., 2012
		Badin et al., 2017
	Indirect grasping task	Bouwsema et al., 2010
		Bouwsema et al., 2012
	Pointing	Bouwsema et al., 2010
Feeding activities	Drinking from a cup	Carey et al., 2008
		Carey et al., 2009
	Slicing	Hussaini et al., 2017
	Stirring	Hussaini et al., 2017
	Eating	Hussaini et al., 2017
	Cutting	Hussaini et al., 2017
		Major et al., 2014
	Carton pouring	Hussaini et al., 2017
Self-care activities	Applying deodorant	Cowley et al., 2016
	Perineal care	Cowley et al., 2016
	Donning zippered pants	Cowley et al., 2016
	Cap task	Metzger et al., 2012
	Clothes task	Metzger et al., 2012

Type of Task	Task	Authors
House-hold activities	Opening a door	Carey et al., 2008
		Carey et al., 2009
	Lifting a box	Carey et al., 2008
		Cowley et al., 2016
	Turning a steering wheel	Carey et al., 2008
	Moving can from a shelf	Cowley et al., 2016
	Moving shoebox from a shelf	Cowley et al., 2016
	Hanging clothes	Hussaini et al., 2017
	Sweeping	Hussaini et al., 2017
	Page turning	Major et al., 2014
	Lifting and transferring weighted object	Major et al., 2014
	Lifting and transferring a tray	Major et al., 2014
	Nut task	Metzger et al., 2012
Clinical task	Box and Blocks	Hebert et al., 2012

Appendix B

Pasta Box Transfer Task

Detailed Task Protocol

This document outlines the set-up and task protocol for the Pasta Box Task.

Last Updated: December 15, 2017

Task Design

This task assesses the ability to reach, grasp, transport, and release a rectangular deformable object (box of pasta) within a standardized table/shelf height set up, at different levels and across midline (Fig 1).

- **Pasta box** dimensions: 7 x 3.5 x 1.5 inches; weight 225 grams CAN (i.e. "Kraft Dinner"); 7.25 ounces/206g US (i.e. "Kraft macaroni and cheese")
- **Shelving unit:** counter height table (36 inch); middle shelf 7 inches from counter top; high shelf 12 inches from counter top (see Appendix A). Neutral eye position marker (reflective marker on orange paper), 18.5 inches from counter top on the front of the middle shelf. Entire shelving unit is 9 inches back from the front edge of the table.
- **Cart** or small table placed to right of shelving unit: 30 inch height
- **Motion capture markers:** placed on table, cart and pasta box as outlined in Task Set-Up

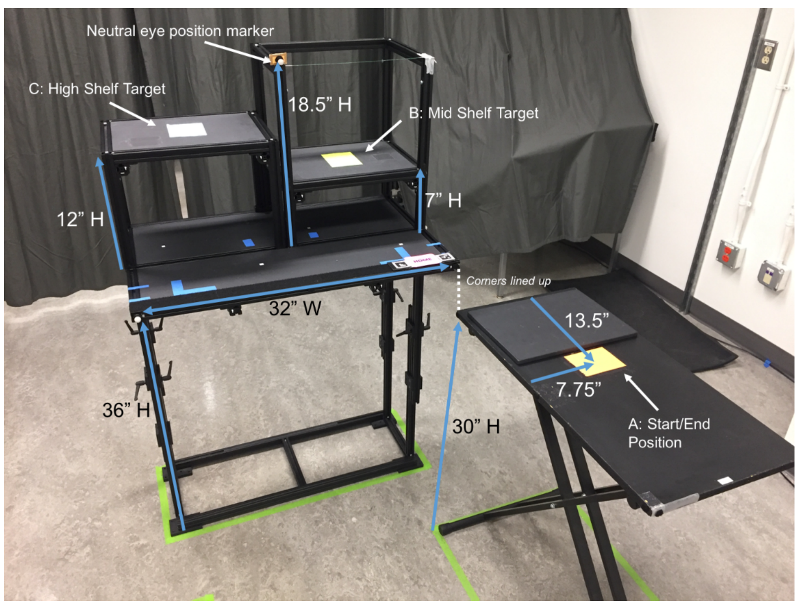


Figure 1. Set up for Pasta Box Transfer Task

Task Set-Up

***NOTE: The following sections are written for a person using their RIGHT hand or terminal device. For testing the LEFT hand or terminal device, positions should be TRANSPOSED.

The shelving unit consists of a counter height platform (36 in high), with a RIGHT side middle shelf 7 inches from counter height (Figure 1, position B) and a LEFT sided high shelf 12 inches from the counter height (Figure 1, position C). Each "Target" position is a 3.5" x 4.5" rectangle. The center of the mid shelf target is 8 inches right of the midline of the able and 15 inches from the front edge of the table. The center of the high shelf target is 8 inches left of the midline of the table and 15 inches from the front edge of the table (Figure 2).

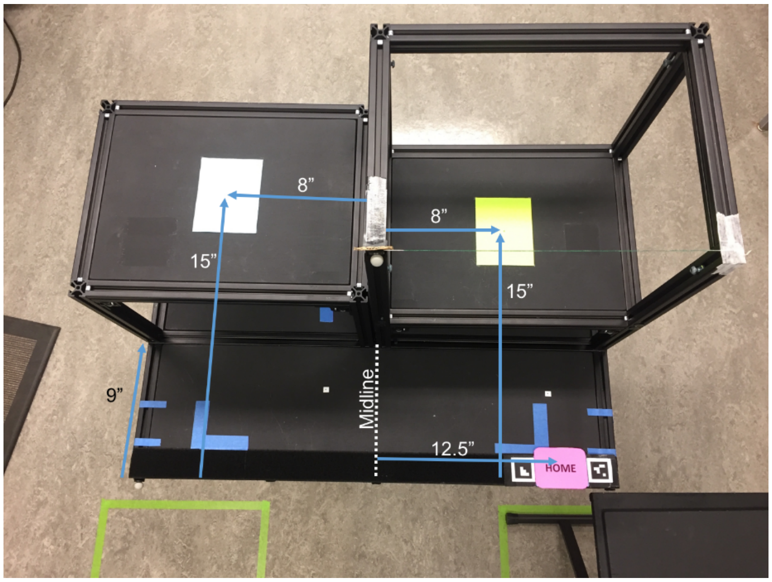


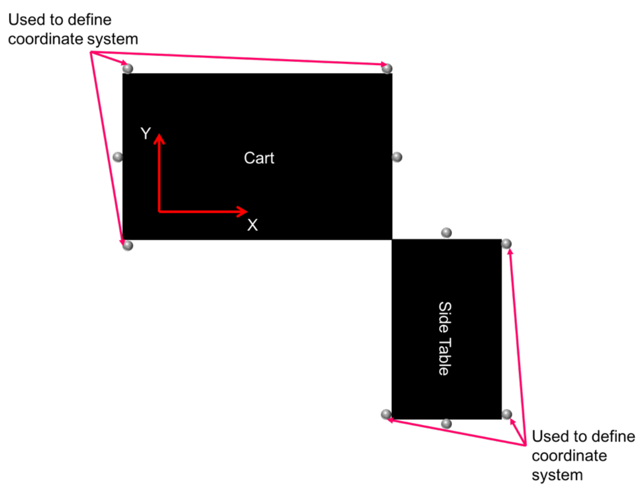
Figure 2. Top View of Set up for Pasta Box Transfer Task

The RIGHT corner of the shelving unit has a HOME sticker (3.25" x 2.5") at the front edge, with its center 12.5 inches right of the midline of the table. The top middle of the shelving unit has a NEUTRAL orange sticker or marker for the participant to fixate on at the beginning and the end of the trial, 18.5 inches from counter height.

The pasta box is placed in a vertical orientation (on its base) on a table 30 inches high to the RIGHT of the shelving unit (Figure 1, position A: Start position). The table is placed so that the LEFT front corner of the table is immediately adjacent to the shelving unit at the RIGHT corner edge (near the HOME position). Relative to the LEFT front corner of the table, the center of the START position target is 13.5 inches to the right and 7.75 inches towards the middle of the table (Figure 1).

The participant stands so that their testing hand/prosthetic terminal device is resting on the standardized HOME position, placed on the RIGHT corner of the counter height shelf, with eyes fixated at neutral, at the start and end of every trial.

Motion capture markers should be placed on the base of the shelving cart, the side table, and the pasta box as indicated in Figure 3.



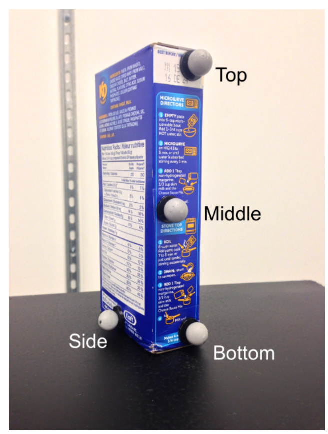


Figure 3. Location of reflective markers for tables (left) and on Pasta Box (right)

Refer to specific protocols for motion capture and eye tracking calibration and data collection process.

Task Overview

The participant will be asked to move the pasta box in 3 discrete transport movements. In-between each grasp-transport-release movement, the hand/terminal device will return to the HOME position.

1. The participant will move the pasta box from the start position to the middle shelf, place the box on its base in the defined target on the shelf, and then return hand to HOME.
2. They will grasp the box from the middle shelf and move it to the high shelf on the LEFT and place it on its base on the target square, and return hand to HOME.
3. Finally, they will move the box from the high LEFT shelf back down to the original starting position and release it on its base, and return hand to HOME.

Task Instructions to Participant

(*Demonstrate the task while explaining*)

Please stand comfortably in front of the cart, so that you can reach the target areas where you will be moving the pasta box. Your body should be centered to the task, and you should try not to take steps to move your body but you can shift your weight. Try to move as naturally as you would in your own environment performing similar tasks.

You will start every trial with the RIGHT hand at the home position and your eyes fixated on NEUTRAL. There are 3 separate movements of the pasta box that we want you perform.

When prompted to start, you will grasp the side of the pasta box, move it up to the middle shelf in the defined **green target** and place it on its base, release, then place your hand back on the HOME sticker.

You will then reach for the box on the middle shelf, grasp it, and bring it over to the top shelf on the left, and release it on its base in the **blue target**. You will then move your hand back to HOME.

You will then reach for the box on the top shelf and move the box back down to the START position on the table to your RIGHT. You will then place your hand back on the home position and look at the neutral eye position to end the trial.

If you drop the box or bump it on anything, continue the movement sequence from where you left off and finish the motion. Make sure that the box is always released so that it is on its base, and not on its side.

I will now demonstrate what the execution of the task should look like *(DEMO full task).*

Perform these movements at a comfortable pace that will allow you to be as accurate as possible, without dropping the box or hitting the edges of the shelving. You will be timed, and errors such as dropping the box or not placing it on the correct edge will be recorded.

Do you have any questions about the task?

You can now practice performing the task. *(Allow practice for minimum 1 trial, or until participant is comfortable with the task)*

(When ready to begin the trials): You will be prompted by the researcher saying "**eyes on neutral, hand on home"** at the start of each trial, then a **"beep"** is the signal that you can start the trial.

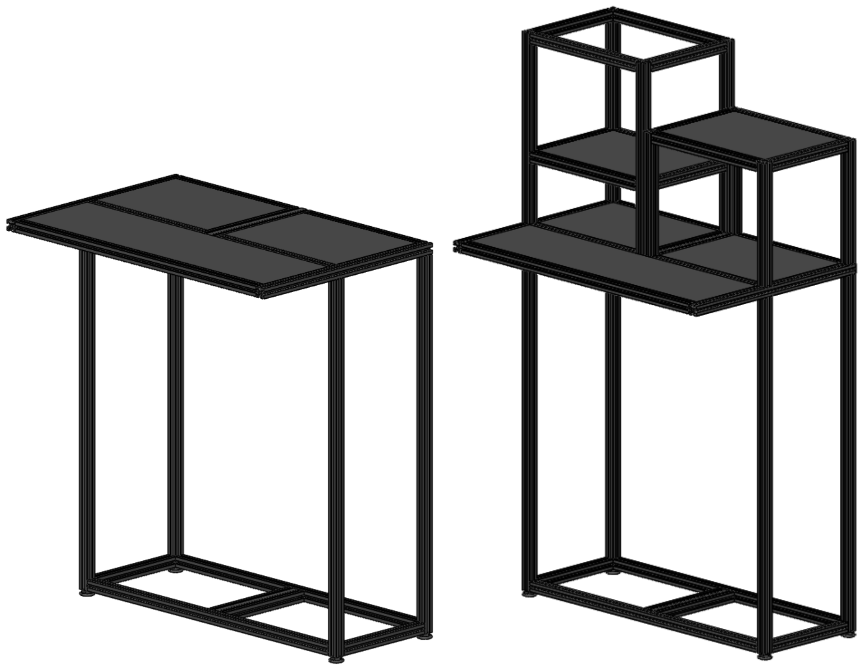
(Follow experimental protocol for # trials)

Performance Metrics

- Time for total task (start and finish at HOME)
- **Errors**: record number and type of errors
  - Dropped box
  - Box grasped incorrectly (i.e. Box was grasped from the top, rather than on the thin side)
  - Box incorrectly placed (i.e. Box was placed on its side versus on its base)
  - Participant hit the frames of cart with the box
  - Incorrect task sequence (i.e. Participant did not go home before moving from position B to position C)
  - Box placed outside of the target (i.e. Pasta box rests half on the target, half off the target)

Appendix A. Task Cart Design

The Task Cart has been designed for use with the pasta box, cup transfer, shape sorting and cup pouring tasks. The design is modular to allow rapid adjustments as needed.



(a) (b)

Fig. A.1 Task cart (a) base, and (b) with shelves

There are several key design features of the task cart that make it useful for the designed tasks.

Shelves are designed to be removed and attached to quickly transition between tasks, while being secure during use. The end of each shelf leg contains a fastener that allows it to slide along the beams on the cart surface, enabling the shelves to slide in and out of the back of the cart. The shelves are secured in place by inserting end caps into the back of the cart beams by hand.

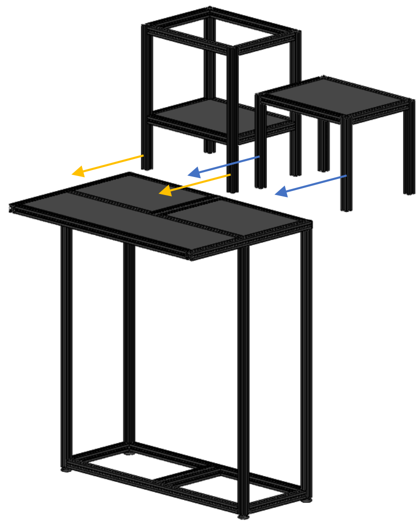


Fig. A.2 Cart with shelves being slid in place from back

The top beam on the tall shelf can be exchanged for a wire, in case the beam interferes with eye fixation areas for the task. There are holes in the shelves to facilitate ease of wire attachment.

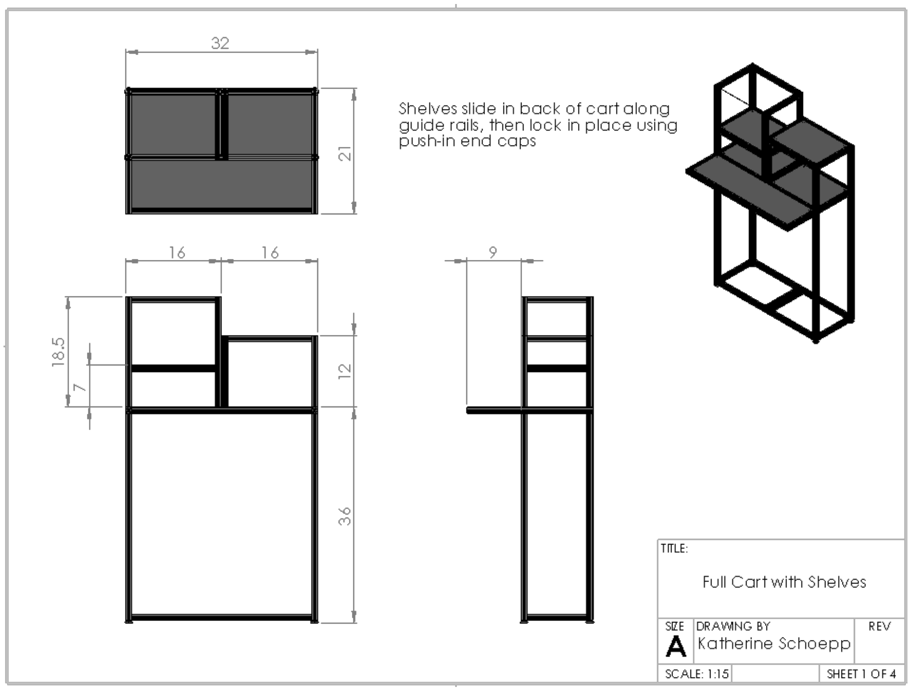
(a) (b)

Fig. A.3 Tall shelf with options (a) beam, and (b) wire

The cart and shelves have been designed using 80/20 slotted framing and can be ordered directly through Rocky Mountain Motion Control by providing them with the following design number: Q000002492. Alternatively, the shelves may be purchased alone.

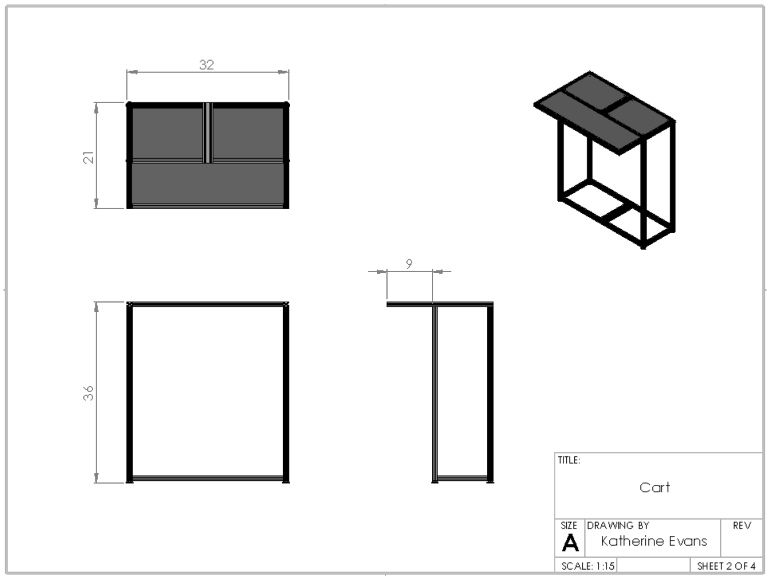
A.2

Drawings are provided below. A SolidWorks model and assembly instructions are available; if desired please contact the BLINC lab.

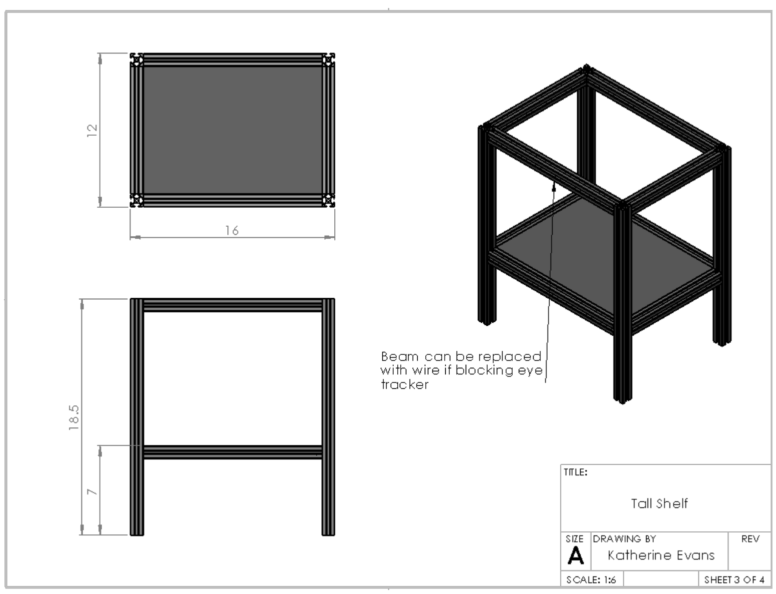


(a)

A.3

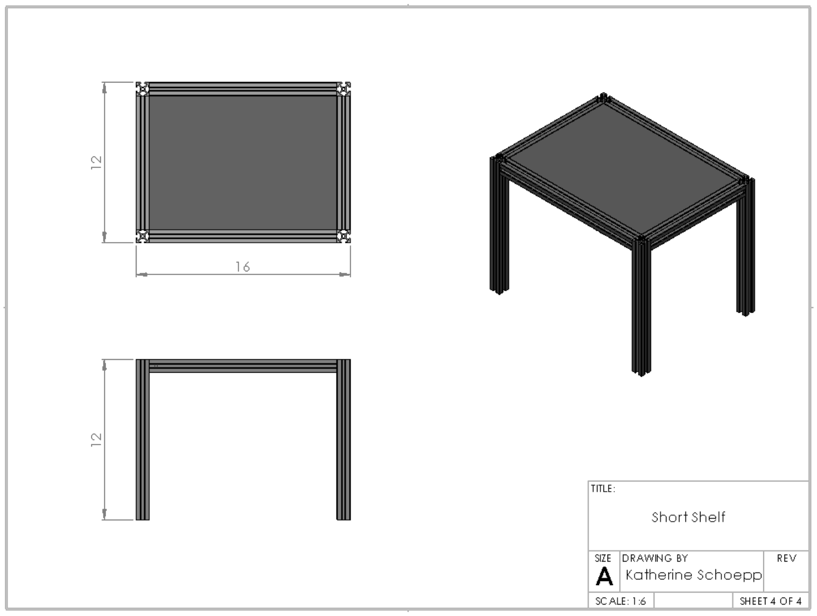

32
21
9
36
TITLE:
Cart
SIZE
A
DRAWING BY
Katherine Evans
REV
SCALE: 1:15
SHEET 2 OF 4

(b)


12
16
18.5
7
Beam can be replaced with wire if blocking eye tracker
TITLE:
Tall Shelf
SIZE
A
DRAWING BY
Katherine Evans
REV
SCALE: 1:6
SHEET 3 OF 4

(c)

A.4



(d)

Fig. A.4 Drawings for designed task cart, (a) full cart with shelves, (b) cart base, (c) tall shelf, and (d) short shelf

Appendix C

Cup Transfer Task

Detailed Task Protocol

This document outlines the set-up and task protocol for the Cup Transfer Task.

Last Updated: December 15, 2017

Task Design

This task assesses the ability to grasp, modulate grasp force (with risk), transport, and release a deformable object across midline in a confined space with pre-determined placement.

- **Box design**: Interior dimensions 30 in. wide, 14 in. deep, 3 in. high box edges, central divider 6 in. high (Figure 1, Appendix A)
- **Targets:** Two defined start and stop targets marked on each side of the box (blue for FAR cup, green for NEAR cup). The centers of the targets are 3 inches from the nearest two box edges (Figure 2)
- **Material:** Two standard 5 oz. Wax Treated Paper Cold Cups (58PATH, Dixie Consumer Products, LLC) filled with beads (Soft Plastic Pellets (A4155 - Phase 2, Patterson Medical Holdings, Inc.) to a weight of 85 grams / 3 ounces (including the weight of the cup)
- **Motion Capture reflective markers:** Placed on the back two corners of the box, and the back top of the middle divider. Each cup should also have a marker as indicated (Figure 3).
- **Table:** Standard counter height (36 inches); box placed 2.5 inches back from the near edge. HOME hand position is on the front edge of the table, with its center 12.5 inches to the right from the midline of the table. "Neutral" eye position marker at back edge of divider, 16.5 inches from the front edge of the table (Figure 1)

Figure 1. Cup Transfer Task Set Up

Task Set-Up

***NOTE: The following sections are written for a person using their RIGHT hand or terminal device. For testing the LEFT hand or terminal device, positions should be TRANSPOSED.

The box is placed on a standard counter height table (36 inches high), 2.5 inches back from the front edge, and aligned with the center of the table. A HOME sticker (3.25" x 2.5") is placed on the right hand side flush with the front edge of the cart, and its middle point 12.5 inches right of the midline of the table. This will be the start and stop position for the hand / terminal device being tested.

A NEUTRAL orange sticker or marker should be placed at the back edge of the divider for the participant to fixate on at the beginning and the end of the trial.

For motion capture (as per *Combined Protocol* document), 2 reflective markers should be placed on the two back corners of the task box, as indicated in Figure 2. In addition, both cups require a marker affixed as per Figure 3.

Within the box, the cups are placed on the side of the testing arm (RIGHT). As per Figure 2, cups are placed in two pre-determined positions, Far (blue targets) and Near (green targets).

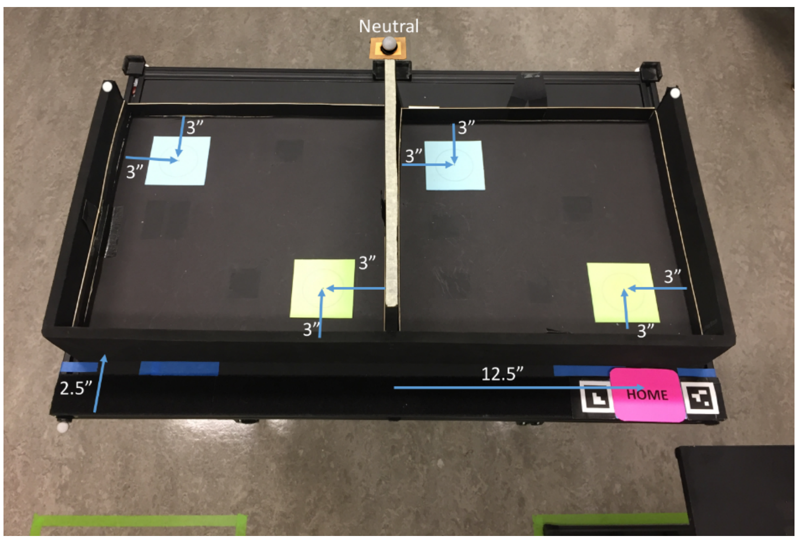


Figure 2. Interior Box Set Up for Cup Task

- **Far position** – The center of the starting FAR target is 3 inches from the back edge of the box and from the partition; the target is colored blue. The corresponding FAR target on opposite side of box (back left corner of left side of box) is also marked blue, its center is 3 inches from back and left sides of box. The blue cup has a colored blue stripe through its center (made with permanent marker).
- **Near position** – The center of the starting NEAR target is 3 inches from the right and the front edges of the box; the target is colored green. The corresponding center of the NEAR target on the opposite side of the box is 3 inches from the divider and the front edge of the box. The green cup has a colored green stripe along the top rim of the cup (made with permanent marker).

Cups are prefilled with the bead pellets, but not overflowing (Figure 3).

- The cups should be prefilled with bead pellets. Place the cup on a weigh scale, and add beads until a weight of 85 g / 3 ounces is reached. At the start of the trial, the cups are placed in corresponding targets on the RIGHT side of the box (side of the testing arm). Note that if a cup is crushed / beads are spilled during the task, a new cup should be inserted for the next trial.

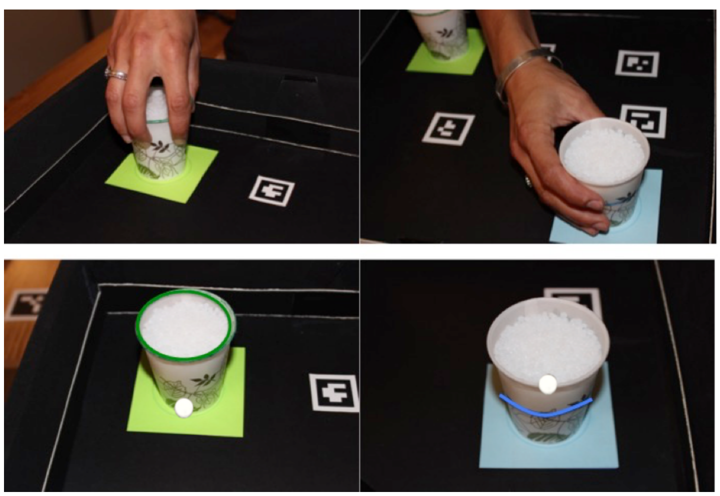


Figure 3. Correct Grasp Patterns and Marker Placement

Refer to specific protocols for motion capture and eye tracking calibration and data collection process.

Task Overview

1. The participant is asked to stand at a comfortable distance away from the table, centered to the task, so that they can reach the cups.
2. They start with their testing hand/prosthetic terminal device on the HOME sticker, and eyes looking at NEUTRAL.
3. When the experimenter instructs the participant (either by saying start, or prompted by a computer beep), they will pick up the NEAR cup first, move it over to the equivalent NEAR target on the left, then return to pick up the FAR cup, and move it to the equivalent FAR position on the left. They will then bring their hand/terminal device back to HOME.
4. They will then reach to the FAR cup on the left and return it to the FAR position on the right side of the divider, and then move the NEAR cup on the left back to the NEAR position on the right side of the divider, and then bring their hand/terminal device back to HOME.
5. Note that the NEAR cup requires a “top” grasp (as prompted by the green rim), and the FAR cup will require a “side” grasp (as prompted by the blue band around the cup), as per Figure 3.
6. One task demonstration by the experimenter and a minimum of 1 practice trial for the participant, is recommended. The number of repetitions for trials is determined based on the specific experimental protocol.

Task Instructions to Participant

(*Demonstrate the task while explaining*)

Please stand comfortably in front of the table, so that you can reach the cups. Your body should be centered to the task, and you should try not to take steps to move your body but you can shift your weight. Try to move as naturally as you would in your own environment performing similar tasks.

You will start every trial with your RIGHT hand/terminal device on the HOME area, and your eyes fixated on NEUTRAL. When prompted to start, you will reach for the NEAR cup with the GREEN rim, grasp it from the top, and move it OVER the partition, and place the cup in the GREEN target area on the other side of the partition. Try not to touch the partition, and you must clear the cup OVER the partition, not around the front. Be sure to place the cup on the target area. Be careful to not drop the cup or spill the beads inside.

Once the NEAR cup has been placed in the target area, move to the FAR cup and grasp it from the SIDE. Lift the cup over the divider, and place it on the BLUE target. After placing this cup on the target area, return your hand/terminal device to the HOME position.

You will then do the reverse of these movements: Reach over and grasp the FAR cup with a side grasp, and bring it back over the divider to the BLUE starting position. Then reach and grasp the NEAR cup with a top grasp, and move it back to the GREEN start position, then return your hand to HOME, with eyes on neutral.

I will now demonstrate what the execution of the task should look like *(DEMO full task).*

Perform this task at a comfortable pace that allows you to be as accurate as possible, without spilling any beads. You will be timed, and the experimenter will record errors such as dropping the cup, spilling the beads, or not placing the cup properly on the target. If you squish the cup or spill the beads, continue the task to the best of your ability.

Do you have any questions about the task?

You can now practice performing the task. (Allow practice for minimum 1 trial, or until participant is comfortable with the task)

(When ready to begin the trials): You will be prompted by the researcher saying "**eyes on neutral, hand on home**" at the start of each trial, then a **"beep"** is the signal that you can start the trial.

(*Follow experimental protocol for # trials*)

Performance Metrics

- Time for total task (start to finish at HOME)
- Number of **Errors**: record number and type of errors:
  - Squished cup
  - Weight of spilled beads: reweigh cup at end of each trial if spillage
  - Dropped cup (will likely need to redo trial, but record error and phase of error – during grasp, transport or release)
  - Incorrectly grasped cup (note grasps may be limited by type of prosthetic terminal device; in this case note type of grasp used).

Note regarding cup compression:

- The gradual force applied to spill beads in an unused cup is approximately 3.9 ± 0.5 N using a side grip, and 4.6 ± 0.6 N using a top grip. This force decreases significantly once the cup rim has cracked (to 3.6 ± 0.4 N and 3.3 ± 0.4 N, respectively), so a new cup should be used for each trial.

Appendix A. Cup Transfer Task Tray Design

The task tray is constructed using a stiff material (so that it does not collapse with pressure), such as Soleflex. The back walls are removable and are held in place using three clamps, 3D printed using a rigid material such as PLA. Solid models of these clamps may be requested. Refer to figures below for dimensions.

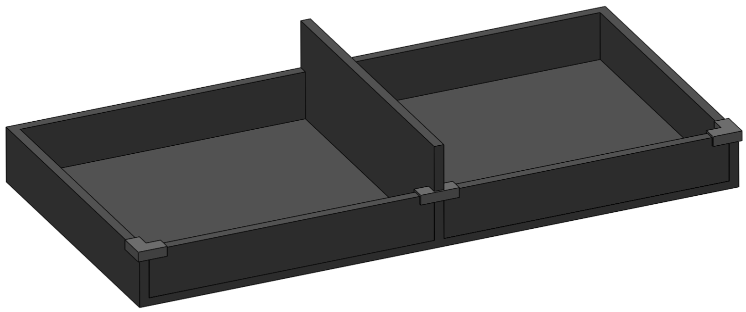


Figure A.1 Back view of tray assembly

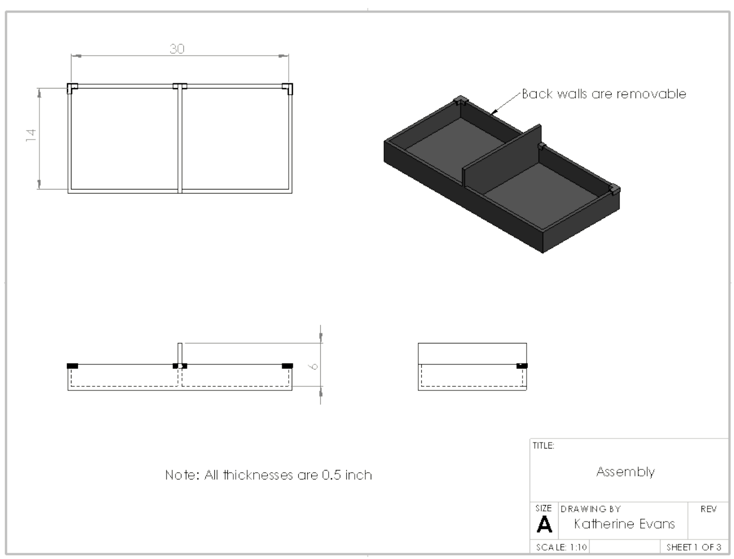


Figure A.2 Assembly of tray components

A.1

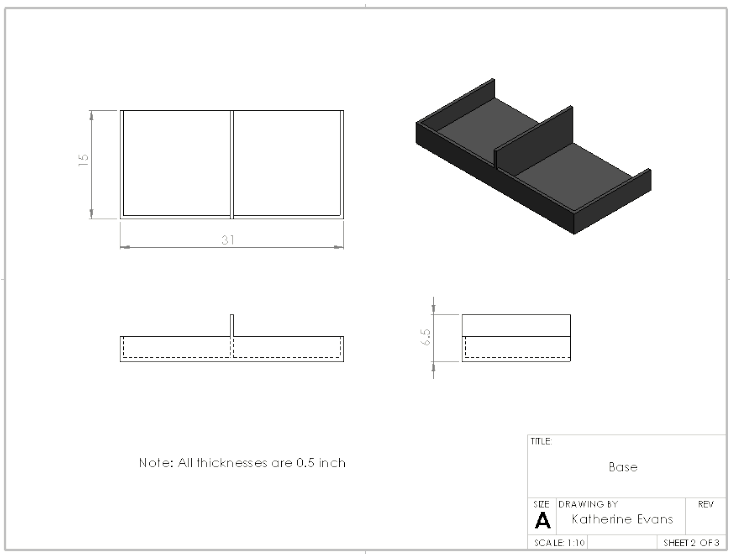


Figure A.3 Base dimensions

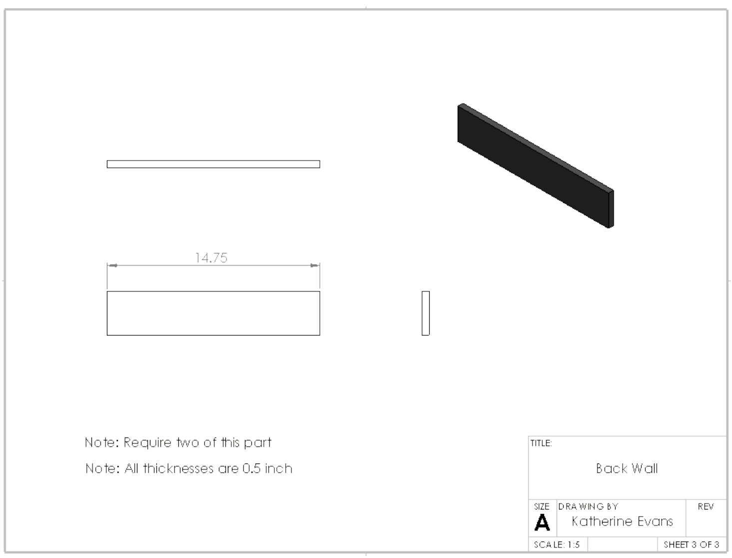


Figure A.4 Back wall

A.2

Appendix D

Pearson Correlation scatter plots for the Cup Transfer and Pasta Box tasks showing the relationship between range of motion and AMULA scores.

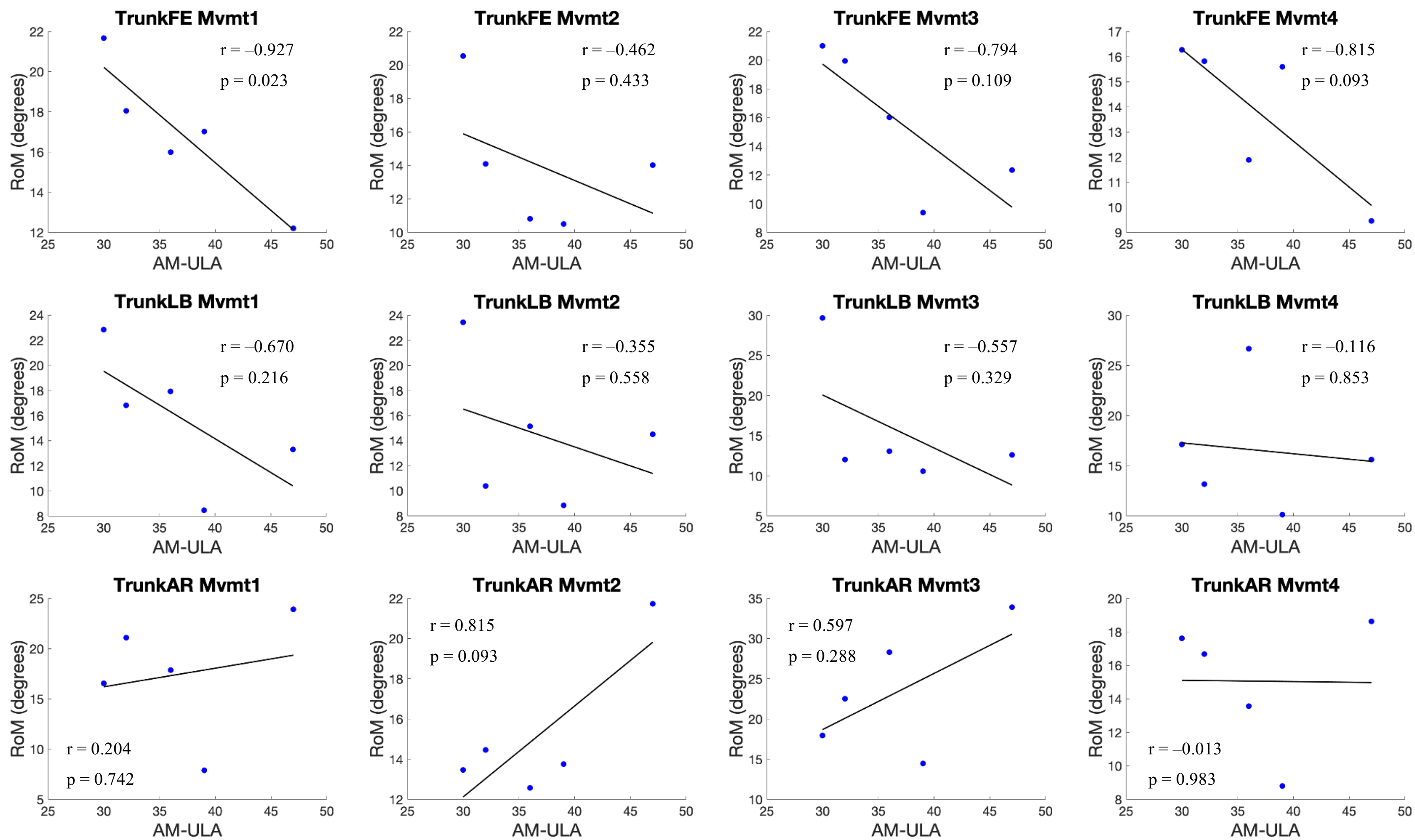


Figure D.1: Cup Transfer task Pearson correlation scatter plots showing the relationship between range of motion and AM-ULA scores (blue dots) for trunk flexion/extension (FE), lateral bending (LB), and axial rotation (AR) for movement 1 (*Mvmt 1*), movement 2 (*Mvmt 2*), movement 3 (*Mvmt 3*), and movement 4 (*Mvmt 4*). *r* indicates the Pearson Correlation coefficient, and *P* indicates the *P*-value for the significance of the coefficient. Significance was set at $P < 0.05$.

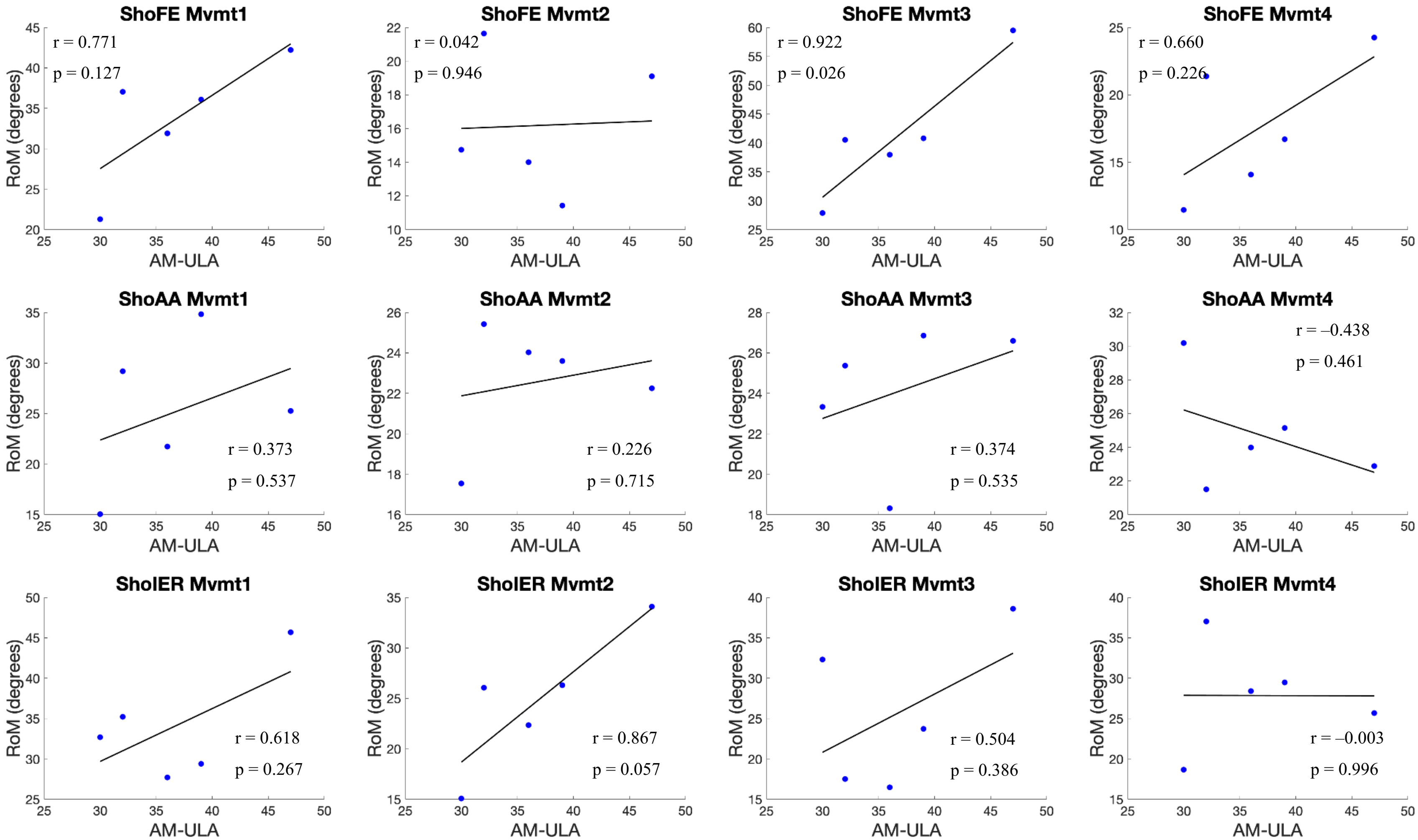


Figure D.2: Cup Transfer task Pearson correlation scatter plots showing the relationship between range of motion and AM-ULA scores (blue dots) for shoulder flexion/extension (FE), abduction/adduction (AA), and internal/external rotation (IER) for movement 1 (*Mvmt 1*), movement 2 (*Mvmt 2*), movement 3 (*Mvmt 3*), and movement 4 (*Mvmt 4*). *r* indicates the Pearson Correlation coefficient and *P* indicates the *P*-value for the significance of the coefficient. Significance was set at $P < 0.05$.

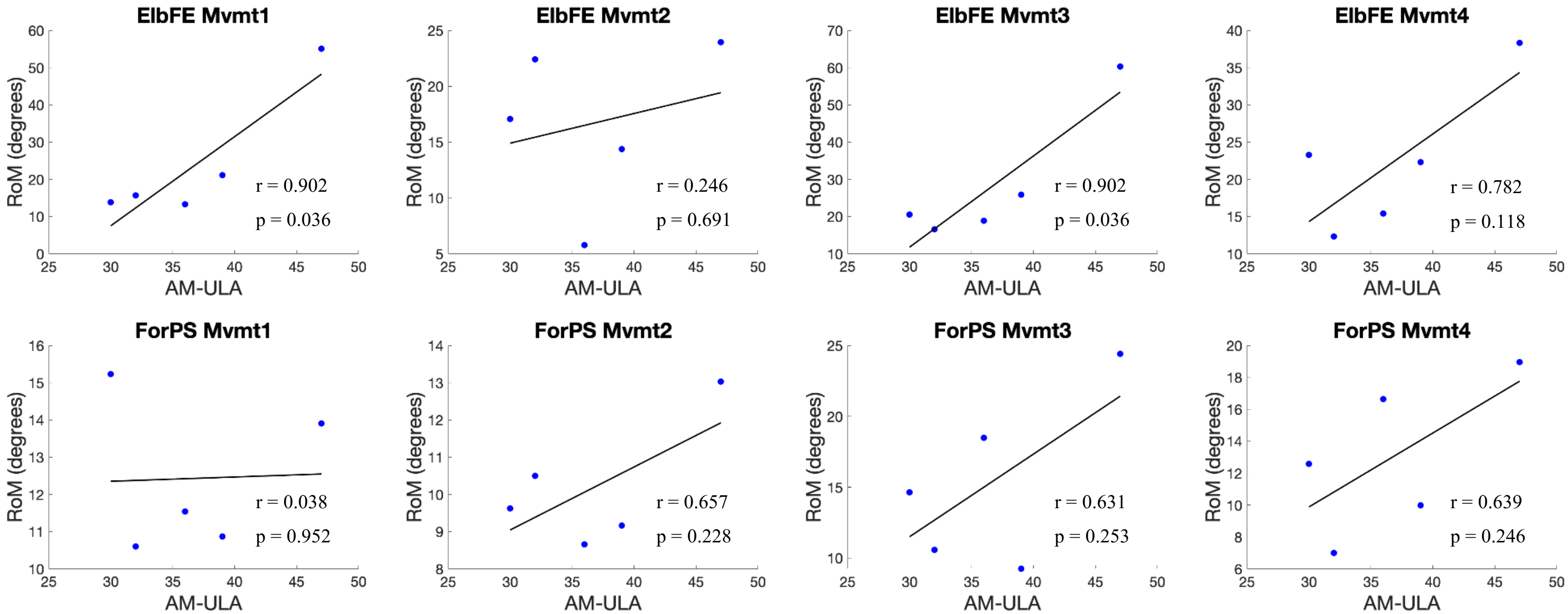


Figure D.3: Cup Transfer task Pearson correlation scatter plots showing the relationship between range of motion and AM-ULA scores (blue dots) for elbow flexion/extension (FE), and forearm pronation/supination (PS) for movement 1 (*Mvmt 1*), movement 2 (*Mvmt 2*), movement 3 (*Mvmt 3*), and movement 4 (*Mvmt 4*). *r* indicates the Pearson Correlation coefficient and *P* indicates the *P*-value for the significance of the coefficient. Significance was set at $P < 0.05$.

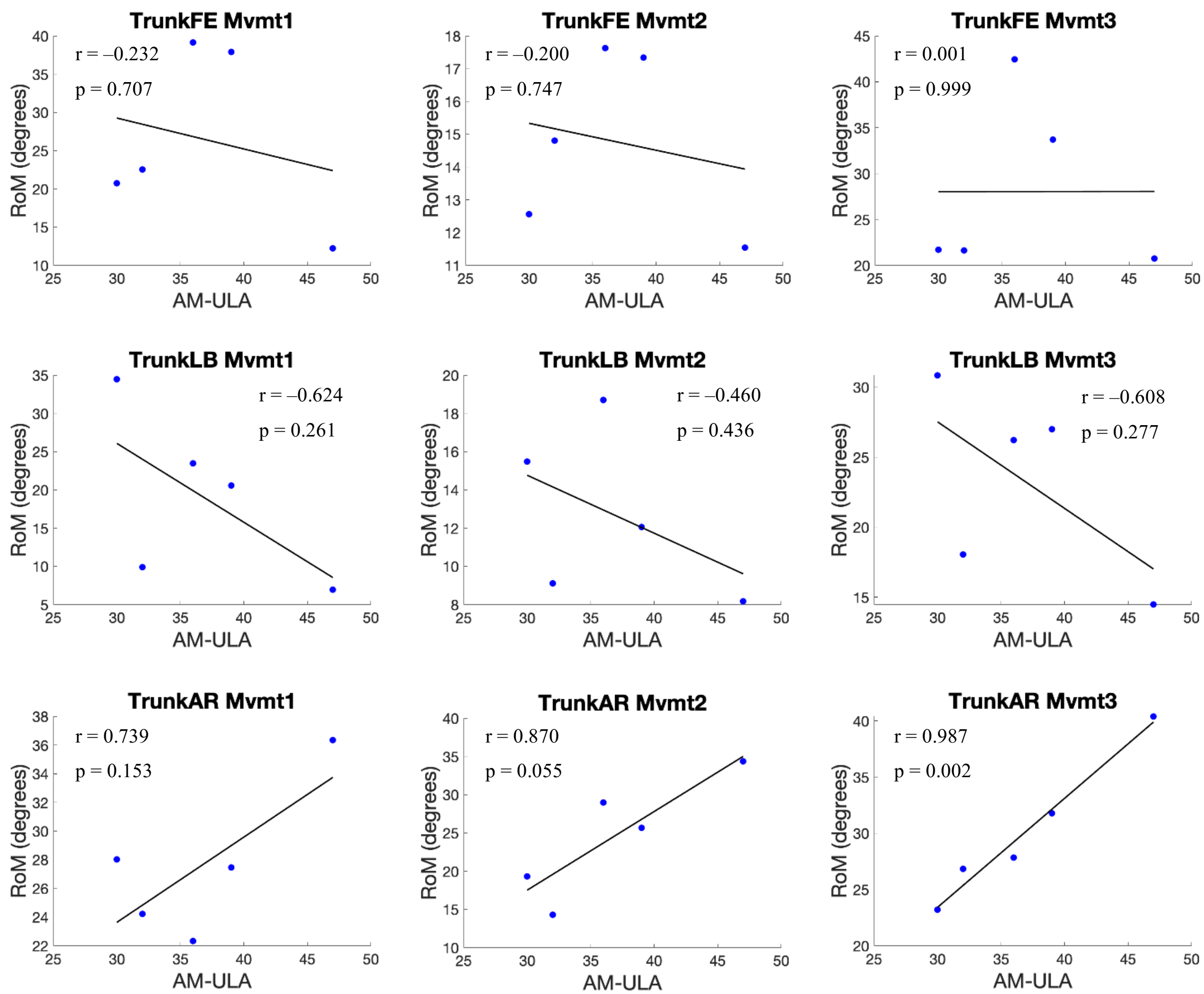


Figure D.4: Pasta Box task Pearson correlation scatter plots showing the relationship between range of motion and AM-ULA scores (blue dots) for trunk flexion/extension (FE), lateral bending (LB), and axial rotation (AR) for movement 1 (*Mvmt 1*), movement 2 (*Mvmt 2*), and movement 3 (*Mvmt 3*). r indicates the Pearson Correlation coefficient and P indicates the P-value for the significance of the coefficient. Significance was set at $P < 0.05$.

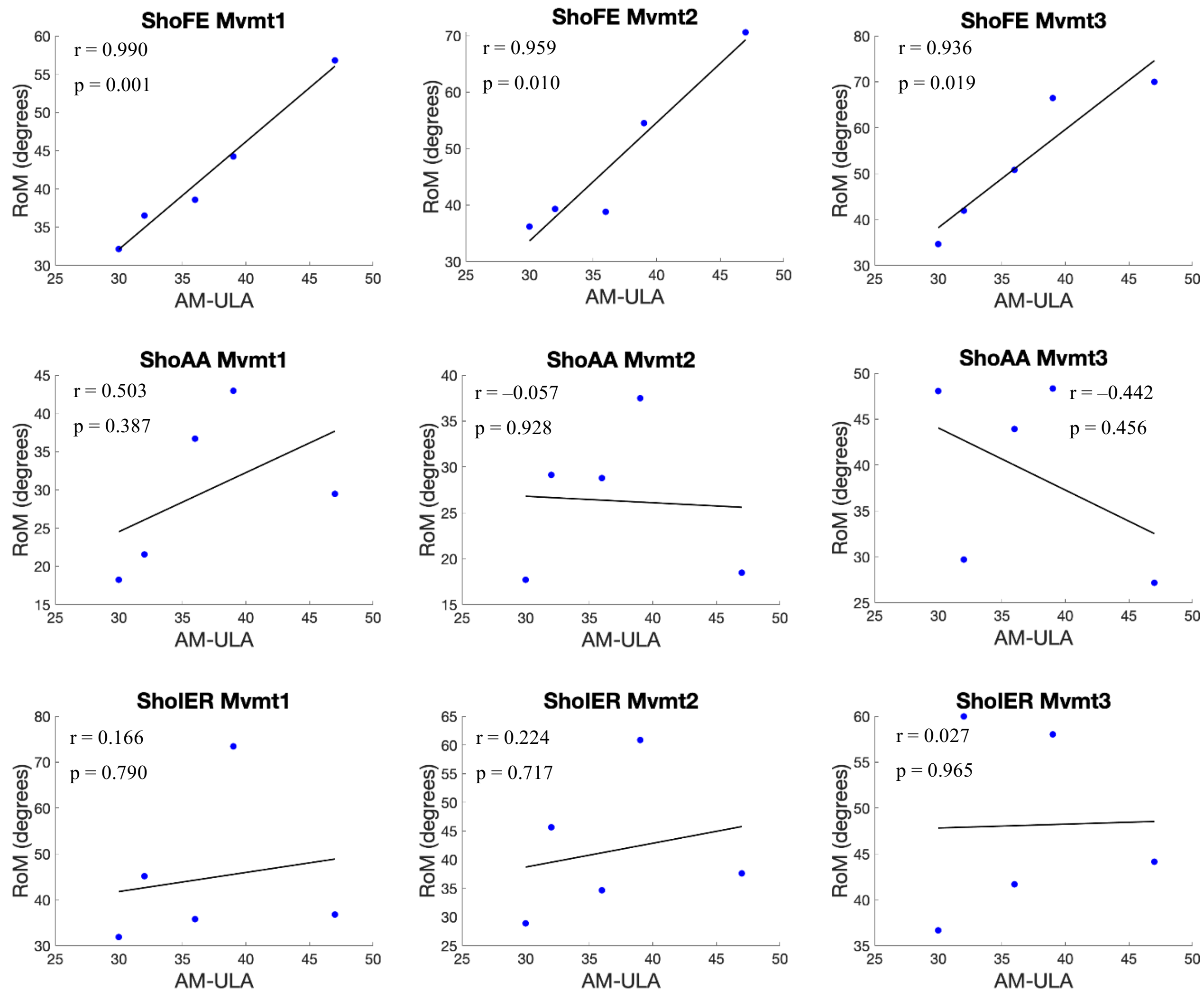


Figure D.5: Pasta Box task Pearson correlation scatter plots showing the relationship between range of motion and AM-ULA scores (blue dots) for shoulder flexion/extension (FE), abduction/adduction (AA), and internal/external rotation (IER) for movement 1 (*Mvmt 1*), movement 2 (*Mvmt 2*), and movement 3 (*Mvmt 3*). *r* indicates the Pearson Correlation coefficient and *P* indicates the *P*-value for the significance of the coefficient. Significance was set at $P < 0.05$.

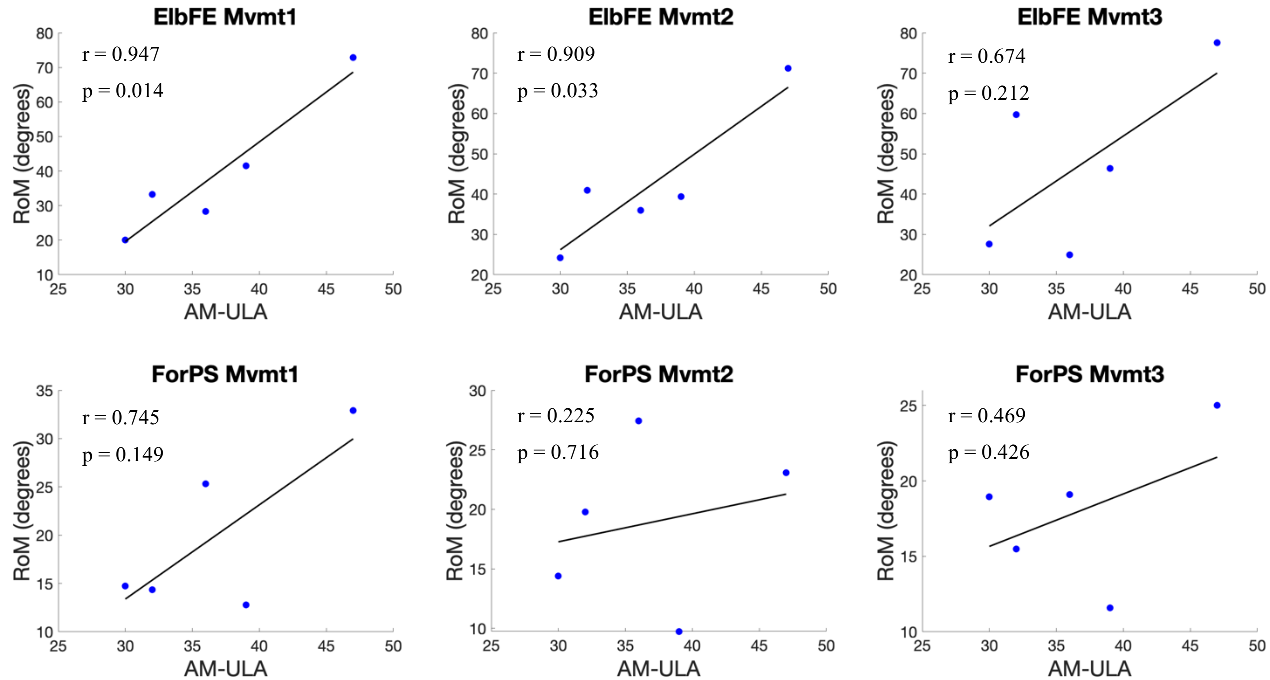


Figure D.6: Pasta Box task Pearson correlation scatter plots showing the relationship between range of motion and AM-ULA scores (blue dots) for elbow flexion/extension (FE), and forearm pronation/supination (PS) for movement 1 (*Mvmt 1*), movement 2 (*Mvmt 2*), and movement 3 (*Mvmt 3*). *r* indicates the Pearson Correlation coefficient and *P* indicates the *P*-value for the significance of the coefficient. Significance was set at $P < 0.05$.