In Search of Manual Asymmetries in Aging during Performance of Activities of Daily Living: Does Upper Limb Performance Become More Symmetric with Age?

by

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A thesis
presented to the University of Waterloo
in fulfilment of the
thesis requirement for the degree of
Master of Science
in
Kinesiology

Waterloo, Ontario, Canada, 2013

AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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ABSTRACT

Introduction: A common disorder arising most frequently after a left hemisphere stroke is limb apraxia. Limb apraxia is a deficit of skilled movement, such as performance of activities of daily living (ADLs), that is not a result of primary motor or sensory impairments, or deficits in motivation, memory, or comprehension (De Renzi, 1990). Currently, clinical neuropsychological assessment of apraxia relies largely on qualitative analyses of gross movements during the performance of activities of daily living in two task conditions (pantomime and tool). Further, apraxic patients often perform ADLs with their non-dominant limb to avoid often-present right-hand hemiparesis, but the assessment does not adequately account for this. Thus, it is unclear whether movement deficits are due to non-dominant limb use or limb apraxia. Moreover, it is not known how different task conditions and aging influence the performance of ADLs in healthy populations, as well as manual asymmetries.

Purpose: The purpose of this thesis was to: 1. determine if age affects the magnitude of manual asymmetry in the performance of two ADLs (drinking water from a cup and slicing a loaf of bread with a knife); 2. determine if different task demands (pantomime and tool condition) affect magnitude of manual asymmetries during the performance of ADLs; and 3. determine if aging affects how task demands are expressed during the performance of ADLs.

Methods: Fifty healthy right-hand dominant (as determined via Waterloo Handedness Questionnaire) younger and older adults participated in this study. A grooved pegboard task was completed by all participants prior to performance of the two ADLs using motion tracking. Upper limb movements (dominant and non-dominant limb) were captured at 60 Hz via a motion capture system (Vicon, Oxford, UK). Participants performed two task conditions: 1) pantomime (pretending to perform an ADL without holding the tool); and 2) tool (pretending to perform an ADL while holding the tool) in two ADLs: drinking water from a cup and slicing a loaf of bread with a knife. Each ADL was performed six times by both limbs. ADLs and limbs were randomized, while task conditions were blocked randomized between participants.

Results: Overall, this study found that aging slows down motor performance on the Grooved Pegboard task, as well as the performance of both ADLs. Manual asymmetries were task dependent. The cup and knife ADL were both characterized by larger manual asymmetries in older adults relative to the younger adult group, particularly in terms of angular movement. Further, it was found that task demands were expressed differently in older adults relative to younger adults, with the tool condition yielding performance improvements in both groups.

Conclusions: Despite the previous research, which has shown that manual asymmetries are reduced in older adults during the performance of motor tasks, this investigation points to the opposite during the performance of activities of daily living. Aging appears to increase the degree to which manual asymmetries are expressed. Further, aging also appears to play a role in the change in temporal and angular aspects of movement during the performance of ADLs in different task conditions. The degree to which task demands as reflected in the two task conditions improve or impair performance in healthy populations should be taken into consideration when evaluating ADL performance in patients with limb apraxia. In accordance with the previous research on aging, this study has shown that upper limb movements become slower as individuals age. Kinematic relationships presented in this study provide researchers and clinicians with an insight into how manual asymmetries, aging and different task demands come into play during the performance of one cyclical and non-cyclical task.

Acknowledgments

I would like to thank my supervisors, Drs. Eric Roy and Clark Dickerson, for all the support they have given me over the course of the past two years. Thank you for believing in this project and for guiding me along the way. I have learned so much from both of you and I cannot even begin to describe how grateful I am to have had such great mentors.

I would also like to thank Drs. Pamela Bryden and Richard Staines for agreeing to be on my committee and believing that I am capable of undertaking such a complex project. Your invaluable expertise has helped make this project what it is today.

To my lab mates, David Gonzalez, James Tung, Carolina Silveira and Sara Scharoun: thank you for being my friends and supporters on this winding road. I would also like to thank Caroline Joseph for her friendship, support and encouragement to keep on going even when things were not going my way. To students who have helped with this project: Aneesha Sravanapudi, Allie Engelhardt, Leah van Draanen, and Tyler Allen, thank you for your dedication and commitment to this project. To Jackie Maciukiewicz, thank you so much for standing in the rain and snow with me to wait for participants, collecting this data with me and for bringing in laughter when it was necessary.

To all my friends: Lucy Yao, many thanks for helping me recruit and taking me trampoline jumping; my whole tennis team (Nicole Holland, Alison Draine, Vanessa Diaconu, Jessica Dam, Courtney Winter): thank you for all the laughs, both on and off tennis court and your invaluable support; UW tennis club members: Rodney Yu, Siddarth Prakash, Daniel Mines and the rest – thank you for your support and laughs along the

way.

Lastly, to my amazing mom, Vesna Tovstonogov, for your unconditional love - you have been my rock throughout this road. Without your support and patience, I would not be where I am today. Thank you for answering the phone at 1am; for listening to me talk about my research for hours on end; for cooking, washing my clothes and taking care of me for the past couple of months; for all the laughs you have shared with me… Thank you for being my best friend and of course, my mom.

Dedication

To my grandpa, Mirko Stantic, for teaching me that 7 x 6 is not 76, but 42.

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LIST OF ABBREVIATIONS

ADL – activity of daily living

PV – peak velocity

TPV – time to peak velocity

TAPV – time after peak velocity

CD – cycle duration

WHQ – Waterloo Handedness Questionnaire

RMSE – root mean square error

DM – dominant hand

ND – non – dominant hand

panto – pantomime condition

tool – tool condition

OA – older adult

YA – younger adult

1.0 Introduction

1.1.Economic impact of stroke and apraxia on upper limb function

Stroke is the leading cause of neurological disability in adults in North America, with a cost of up to $3.6 billion per year to the Canadian economy (Heart and Stroke Foundation, 2010). In 2009, indirect costs associated with disability ($121.2 million) and premature death ($279.6 million) corresponded to 38.3% of the total cost of stroke in Ontario (Tarride et al., 2009). Approximately two thirds of stroke survivors are left with residual neurological deficits that impair upper limb functioning and half are left with disabilities that make them dependent on others for activities of daily living. Further, only 5% of adult stroke survivors regain full function of the upper limb, while 20% regain no functional use of it (Heart and Stroke Foundation, 2012). A common disorder arising most frequently after a left hemisphere stroke is apraxia (Zwinkels et al., 2004). Limb apraxia is a deficit of skilled movement that is not a result of primary motor or sensory impairments, or deficits in motivation, memory, or comprehension (De Renzi, 1990).

In clinical settings, left-hemisphere stroke patients suspected of exhibiting limb apraxia are typically assessed using a neuropsychological battery, such as the Waterloo-Sunnybrook Apraxia Battery (please see Stamenova et al., 2010), which consists of disparate gestures and activities of daily living (ADLs), such as driving a hammer to pound a nail, as well as different task conditions, such as the pantomime (tool not present while performing an ADL) and tool conditions (performing an action with the tool). Due to the hemiparesis of the right hand (dominant limb) caused by the left hemisphere stroke, patients are asked to perform gestures and ADLs from the Waterloo-Sunnybrook

Apraxia Battery with their non-dominant (left) limb (Stamenova et al., 2010; Wheaton et al., 2007). However, the assessment does not adequately account for the involvement of the non-dominant limb in the performance of ADLs. It is unclear therefore whether errors observed during the performance of ADLs in apraxic patients are due to the non-dominant (left) limb control or actual performance impairments resulting from the disorder. Hence, it is important to investigate in detail how manual asymmetries may affect performance of ADLs. Since apraxia assessment assesses the use of tools, manual asymmetries should be evaluated in the context of tool use or use phase of movement. Further, since stroke most often affects adults over the age of 65 (Heart and Stroke Foundation, 2012), these asymmetries need to be investigated in the context of aging.

The specific objectives of this study are to:

1) Establish the influence of manual asymmetries on the use phase in pantomime and tool task conditions during the performance of two ADLs (knife and cup ADL) in healthy younger and older adults;

2) Examine how aging affects the use phase during the performance of cup and knife ADLs in pantomime and tool task conditions; and

3) Determine whether aging affects manual asymmetries in the use phase of movement in pantomime and tool conditions.

Long-term apraxia assessment objectives are to examine whether manual asymmetries need to be considered during apraxia assessment. Ultimately, the goal of this research is to aid in understanding of manual asymmetries and aging during the performance of ADLs in different task conditions.

2.0 Literature Review

Kinematic Details of Tool Use

2.1.1. Tool acquisition: General overview on reach to grasp movements

Reach-to-grasp movements can be divided into two phases: 1. Reaching phase, where the participant initiates a movement and reaches for an object/tool in front of them; and 2. Grasping and manipulation (or use) phase, where an individual grasps the object/tool and performs an action associated with it. The most common conceptual framework (Lovelace, 1990) for analysis of these movements proposes that the information from the environment is attained, serving as an input to the perceptual-motor system and consequently, processed through a number of different stages to elicit an appropriate motor response. In examining motor responses, this approach relies on temporal measures, such as the reaction time (RT) and movement time (MT). Reaction time represents the time it takes to initiate a movement, while the movement time reflects the time required to execute the movement.

Once the movement is initiated, processes of movement execution are derived from movement time and divided into two principle stages: a ballistic or pre-programmed stage and a feedback stage (Woodworth, 1899). The initial, ballistic phase of reaching for an object is considered to be under open-loop control (feed-forward or anticipatory control) (Woodworth, 1899). Feed-forward control of movement requires a generation of an internal model for accuracy and does not rely on sensory information received during the movement (Seidler et al., 2004). This phase of movement represents motor program's efficiency for planning a motor response (Meyer et al., 1988). Time to peak velocity

(TPV) represents feed-forward control, which involves initiating changes in the movement in anticipation of changes in the future (Roy, 1996). Feedback control comes into play once the limb is in the region of an object/tool (phase after PV). In this phase, visual information about the relative position of the limb and the object/tool is used to make any adjustments to the movement trajectory necessary to grasp the particular target. This type of control is therefore important for generation of highly accurate movements, as well as error detection and correction (Seidler et al., 2004). To achieve a highly accurate movement, feedback control uses sensory feedback loops, allowing for corrections at the very end of the trajectory, when the velocity decreases (Desmurget et al., 2000). This control uses current information to initiate a corrective pattern in ongoing movement (Roy et al., 1994). Time after peak velocity (TAPV) is associated with online or feedback control (Cooke et al., 1989). Meyer et al. (1988) found that when movements require increased spatial accuracy, such as reaching towards a smaller target, time spent after peak velocity increases. This increase in TAPV reflects greater dependence on response-produced feedback for accuracy (Chua et al., 1993; Heath et al., 1999). Optimal movement control therefore is likely reflected as a combination of feed-forward and feedback processes (Desmurget et al., 2000).

Interaction with the external environment is highly dependent on our ability and knowledge to manipulate tools and objects. For example, in the morning one would brush their teeth with a toothbrush, comb their hair with a comb and stir coffee with a spoon. Manipulation of tools represents a highly skilled and learned movement. However, research to date has mostly focused on kinematics of reaching movements. Research examining the kinematics of use phase in healthy younger and older adults has received very little attention in the literature to date.

2.1.2. Use phase in pantomime and tool task conditions

Pantomime and tool task conditions are of fundamental importance in the evaluation of limb praxis. Pantomime condition, typically, involves performance of a gesture to a verbal command without visual and non-visual (ie. haptic, kinaesthetic) information about the tool. For example, a stroke patient is asked to show the clinician how they would use a hammer to pound a nail, without the physical presence of the hammer and/or a nail. On the other hand, the tool condition consists of performing an ADL while holding the tool. In this case, the clinician asks the stroke patient to perform an ADL with the physical tool.

Pantomime is currently the most sensitive measure to detect apraxia in left-hemisphere stroke patients (Goldenberg, 2003), as errors in gesture production are particularly pronounced in these patients during pantomime condition (Hermsdorfer et al., 2011; Randerath et al., 2011; Buxbaum et al., 2000). Pantomiming to a verbal command requires access to stored action representations in response to minimal information stimuli, as well as contextual support (Frey et al., 2008). Kinematically, pantomiming a gesture tends to be characterized by high peak velocities (Clark et al., 1994; Hermsdorfer et al., 2011; Heath et al., 2002), higher range of motion at the wrist, elbow or shoulder joints (depending on the gesture performed) (Randerath et al., 2011; Hermsdorfer et al., 2012; Clark et al., 1994; Poizner et al., 1995; Hermsdorfer et al., 2006) and larger movement amplitude (Randerath et al., 2013) as opposed to the tool condition. This exaggeration of movement in pantomime is said to be potentially due to its communicative nature (Hermsdorfer et al., 2006). An individual will make the motor action more pronounced so that the receiver would understand the meaning of it.

Tool condition, on the other hand, relative to pantomime, has been shown to improve ADL performance as reflected in spatial (e.g. plane of movement, reduced range of motion at the joint) and temporal adjustments (e.g. modifications in speed of movement) (Clark et al., 1994; Hermsdorfer et al., 2006; Hermsdorfer et al., 2012). Advantage for the tool task has been thought to arise due to the presence of the tool (e.g. hammer) facilitating access to the motor program involved in using the tool (Randerath et al., 2009). In this case, the tool is defined as the device, which is used to perform a certain action, while an object is a device on which the tool is acting. A study by Clark et al. (1994) has suggested that addition of an object (i.e. nail) but not the tool (i.e. hammer) improves performance of the ADL. In their study of three apraxic patients and four neurologically intact individuals, it was found that addition of the tool only, did not improve performance of apraxic patients while performing a “slicing” gesture. However, once the object and the tool were provided (i.e. bread and knife) to both controls and patients, the performance of the ADL improved as characterized by scaling of cycle duration and peak velocities. They argued that the information that the object provides is more important, and thus, drives the performance of the task, while the addition of the tool provides very little information (Clark et al. 1994). Therefore, according to this view, providing just a tool to the apraxic patient, such as used in the Waterloo-Sunnybrook Apraxia battery, should not elicit an improvement in ADL performance.

On the contrary, in their study, Heath et al. (2002) found that providing only a tool to healthy younger adults changes the performance of a “slicing” gesture. Specifically, they found a reduction in peak velocities, as well as movement amplitude. Since this is the only study that investigated the influence of task conditions on the performance of ADLs in healthy adults, it is important to determine whether partial somaesthetic cues (e.g. presence of only the tool) provide enough information for improved performance of ADLs, as well as how do they impact the performance in healthy younger and older adults.

2.1.3. Joint coordination in use phase

Temporal (ex. TPV, PV, TAPV) and spatial (e.g. range of motion) aspects of movement as described above give us some insight into how gestures are performed and which parameters may differ between hands and deteriorate in aging. However, these do not tell us anything about interjoint coordination, or lack of coordination, in terms of individual limb segments.

Joint coordination deficits are documented in apraxic patients. Poizner et al. (1995) constructed a kinematic analysis of repetitive slicing gestures in pantomime and tool conditions in three apraxic patients and four neurologically intact males. To quantify degree of synchrony in motion between shoulder, elbow and wrist, Poizner et al. described these motions by utilizing linear regression techniques. Overall, controls in this study performed smooth movements with generally linear relationships between elbow and wrist velocity regardless of the condition (Figure 1). The correlations between wrist and elbow velocities were found to cluster between 0.95 and 1.0 regardless of the condition or trial number. High correlations suggested a high degree of synchronized interjoint motion and a consistently tight relationship between the two dependent measures. Hence, the rate of change in wrist velocity was almost equal to the rate of change in elbow velocity. Further, the somewhat parabolic relationship seen in Figure 1 between elbow flexion/extension and linear wrist velocity helps keep the wrist in the sagittal plane (e.g. forward/backward axis). Controls also produced smooth sinusoidal curves in terms of joint angles at the shoulder, elbow and wrist in both conditions. For example, as the elbow extended, the upper arm moved medially, while the forearm moved laterally in the horizontal plane. Controls also utilized greater elbow flexion/extension relative to both shoulder elevation and shoulder plane of elevation.

Speed at the elbow is controlled by motion of the shoulder, while speed at the wrist is regulated by combined motions of the shoulder and elbow joints. Previous studies have shown that healthy controls have tight coupling between shoulder and elbow joint motions (Lacquaniti et al., 1982; Sainburg et al., 1993). Sainburg et al. (1993), for example, found that increases in elbow flexion/extension happen synchronously with increases and decreases in shoulder elevation and shoulder plane of elevation in a slicing gesture. Further, elbow and shoulder joints reverse the direction of the movement simultaneously. This was also shown by Kelso et al. (1991), who looked at single limb multi-joint movements. Tight spatiotemporal pattern was found between the elbow and the wrist joints. It was hypothesized that these patterns of joint coordination constrain segments and may serve as a mechanism to simplify neuromuscular control of a biomechanical system with multiple degrees of freedom (Poizner et al., 1995).

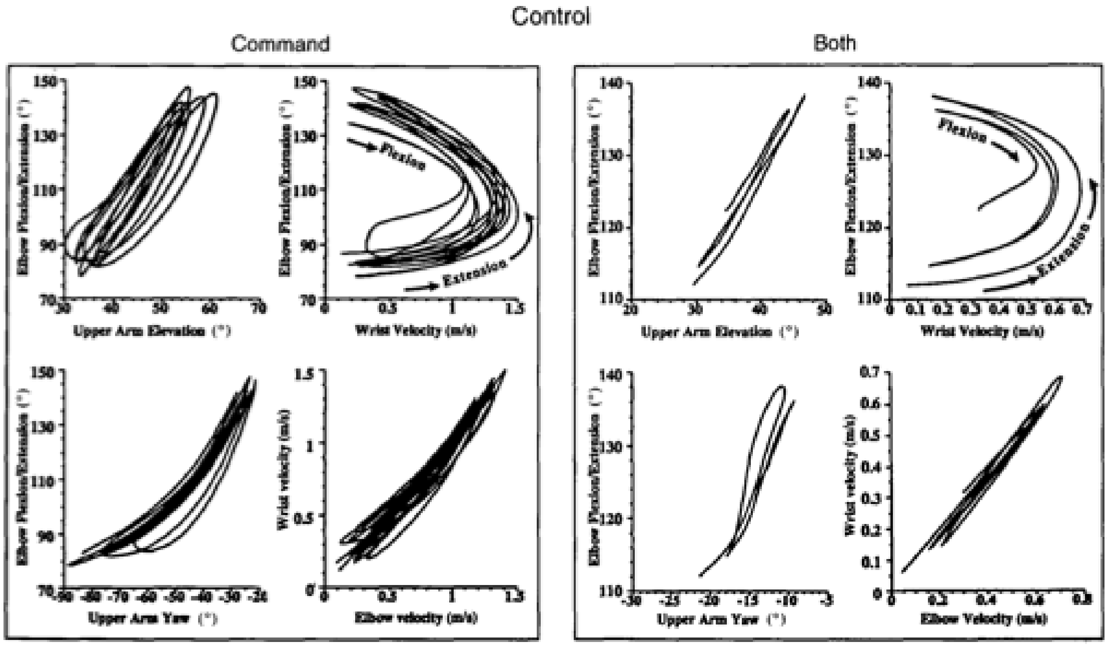


Figure 1: Kinematic relationships between arm angles and wrist and elbow velocities in a healthy control in pantomime (left) and tool (right) conditions (Poizner et al., 1995).

Patients with apraxia, on the other hand, produce distorted angle to angle, velocity to velocity and angle to velocity relationships across conditions (Figure 2). Diminished upper arm elevation and reduction in elbow flexion/extension was observed in some patients (Poizner et al., 1995). Instead of a smooth movement, the movement produced by a patient was described as “choppy”. Further, there was high variability and inconsistency in the relationship between elbow flexion/extension and wrist velocity. Hence, an irregular relationship, characterized by correlations between 0.5 and 0.9 between elbow and wrist velocities, was present in apraxic patients.

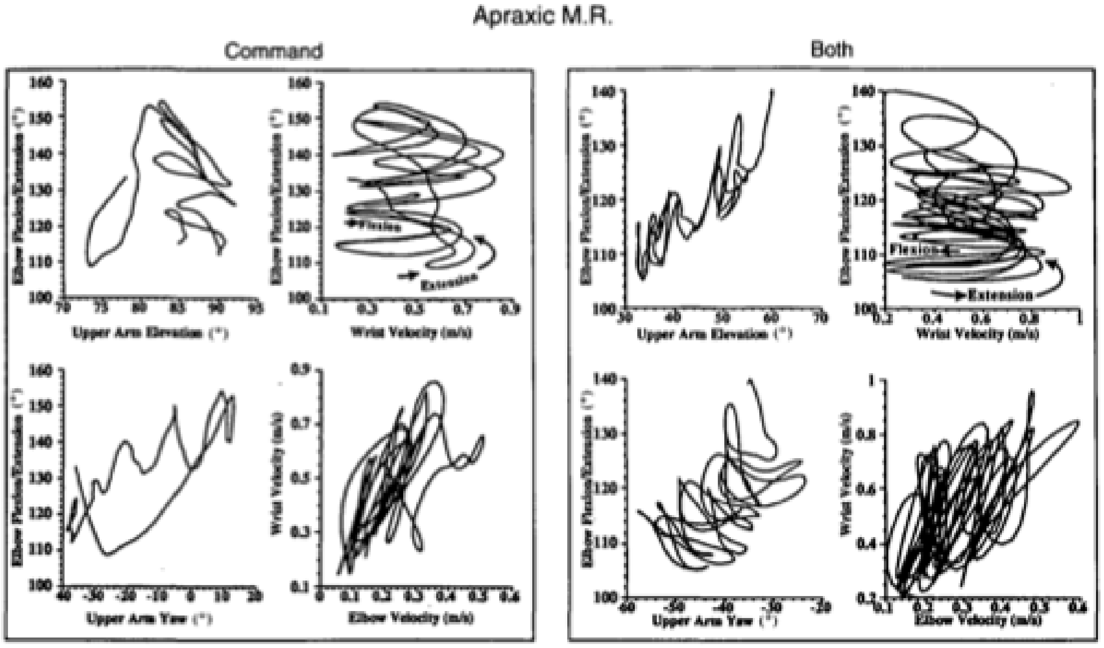


Figure 2: Kinematic relationships between arm angles and wrist and elbow velocities in apraxic patient in pantomime (left) and tool (right) conditions.

Interjoint coordination in drinking from a cup ADL in stroke patients was examined kinematically only in one study, which focused on the reach phase of movement. Murphy et al. found that relationships between elbow flexion/extension, shoulder flexion/extension, and shoulder abduction/adduction (frontal plane) yielded lower correlations (between 0.51 to 0.98) in a group of patients affected moderately by stroke relative to the healthy controls (0.89 to 0.99) (2011). Since the use phase, hand differences, different task conditions, and age effects were not investigated in this study, it is unclear as to how or whether interjoint coordination changes as a function of hand, task or age.

Although kinematic relationships between arm angles and joint velocities in healthy populations have been investigated in the context of apraxic and deafferentated patients, very little attention has been given to the investigation of the same relationships in the use phase between dominant and non-dominant limbs and how these variables change due to aging in healthy younger and older adults.

2.2. Manual Asymmetries

2.2.1. Manual asymmetry assessment via questionnaires and performance measures

Currently, hand preference can be measured using questionnaires, such as the Waterloo Handedness Questionnaire, or motor tasks, such as the Grooved Pegboard. Hand preference questionnaires usually ask participants a number of questions regarding which hand they prefer to use to complete a number of different tasks, such as writing, holding a toothbrush, or turning on a light switch. However, assessing hand preference is much more complex than asking a participant with which hand do they usually perform an action. There exists a degree of handedness (ie. strongly right handed, versus only moderately right-handed) (Annett, 1976). To make up for this, researchers have included a range of options in the questionnaire, such as “always” or “usually” use right/left hand for performance of a task. However, questionnaires, such as the Waterloo-Handedness questionnaire, represent a subjective method to assess handedness. One of the concerns of using a questionnaire is that an individual has to recall with which hand they would perform a task. Performance measures, such as a grooved pegboard, are not susceptible to this problem and thus, represent a more objective way to determine handedness.

Relationships between self-reported hand preference (ie. questionnaires) and performance measures have been investigated. A strong correlation was found between preference and performance on peg moving and finger tapping (Annett, 1976; Peters, 1998). In his study, Peters investigated the relationship between handedness questionnaires and different unimanual tasks, including the Annett peg-moving task, the Grooved pegboard task, a finger tapping task, a movement sequencing task, and two O'Connor dexterity tasks (tweezers and fingers). He found that scores on the handedness questionnaires are strongly correlated with all of the motor tasks. Thus, individuals who have larger manual asymmetries between the limbs display this while performing different tasks relative to those who are, for example, more ambidextrous. More recently, Brown et al. (2006) found that Waterloo-Handedness Questionnaire significantly correlated to the Grooved Pegboard's place task, Wathand Box test, Annett pegboard, finger tapping and grip strength. In this thesis, one focus of interest is on how the self-reported hand preference measures and performance measures correlate with kinematic variables quantified during the performance of ADLs.

2.2.2. Asymmetries in motor performance

Manual asymmetries in upper limbs are present during the performance of motor tasks. The term manual asymmetries, refers to the differences in the performance between the two limbs. Woodworth (1899) assessed the ability of participants to perform a repetitive line-drawing task with dominant and non-dominant hands. In his study, movements of the dominant hand were substantially more accurate (lower absolute error) than those performed by the non-dominant hand. This asymmetry was further enhanced when participants were asked to perform the movements as quickly as possible, with non-dominant limb producing a less accurate movement.

Subsequent studies on manual asymmetries in upper limbs demonstrated numerous right hand advantages in motor control. When quantifying manual asymmetries in finger tapping and repetitive finger flexion/extension movements, the dominant limb was found to have higher speeds and consistency (Todor et al., 1982; Peters, 1976). Further, in fast, repetitive tapping tasks, a consistent preferred hand advantage has been reported in children (Fagard, 1987) and younger adults (Teixeira et al., 2000). Right-hand advantage is also evident during handwriting (Blank et al., 2000) and aiming at static targets (Sainburg, 2002). Further, movement times tend to be shorter in the dominant limb relative to the non-dominant limb during rapid aiming movements and unimanual reaching tasks (Annett et al., 1979; Roy et al., 1989). Non-dominant limb movements are typically associated with shorter time to peak velocity values (Roy et al., 1994). Further, research on aiming, reaching, and pointing has found that the dominant arm achieves higher peak velocities (Annett et al., 1979; Boulinguez et al., 2001; Heath et al., 2000), smaller errors in initial acceleration phase of movement (Roy et al., 1986), shorter movement time and better accuracy (Elliott et al., 1993). The non-dominant arm, on the other hand, has shorter reaction times (RTs) (Elliott et al., 1993; Carson, 1992). However, symmetric performance between the hands has been observed in tasks requiring the grasp of moving objects (Teixeira, 1999) and anticipatory timing (Teixeira, 2000).

Previous research has described manual asymmetries in upper limbs through feedback and feedforward modes of control. For example, it has been shown that the dominant arm is more specialized in speed of processing visual and proprioceptive feedback (Roy, 1983; Roy et al., 1994). It has been hypothesized that the dominant arm, therefore, is better suited for feedback control. In contrast, the non-dominant arm has been said to be better suited for movement planning (ie. feedforward control) (Carson et al., 1993). However, more recently, an opposite framework has emerged, stating that the dominant system uses feedforward processes, while the non-dominant system utilizes feedback mechanisms (Haaland et al., 1994; Hermsdorfer et al., 1999). Therefore, the exact specialization in terms of feedforward and feedback loops remains controversial.

A more recent theory regarding manual asymmetries, also known as the dynamic dominance theory, states that the dominant limb is important for controlling limb dynamics, such as direction of movement and trajectory shape; while the non-dominant limb is specialized for the control of limb position (Sainburg, 2002, 2005). Rather than describing the right hand-left hemisphere system as more advantageous than the left hand-right hemisphere system, it could be said that the control of both limbs has become distributed between the two systems (Wang et al., 2007). The left (non-dominant) hand is better suited for stabilization of objects or postural orientation tasks, where the limb does not need to acquire higher intersegmental dynamics, since the trajectory is not fundamental to complete the task (Sainburg, 2002). For example, when slicing a loaf of bread with a knife, the non-dominant hand would stabilize the loaf of bread, while the dominant hand would through gross movement control direct the knife to slice the bread. The use of the dominant limb is associated more with activities that require precise movements and specific trajectory formation (Healey et al., 1986), such as using a hammer as accurately as possible to hit the nail on its head.

Dominant limb is specialized in trajectory formation. Evidence for this specialization was first revealed when comparing coordination patterns between the two limbs in targeted reaching task (Sainburg et al., 2000). Participants were asked to reach to targets while the amount of elbow displacement was held constant at 20°, but the amount of shoulder excursion was varied between 5°, 10° and 15°. In the dominant limb, Sainburg et al. quantified straight-line hand path trajectories, suggesting a use of a more proficient interlimb torque pattern, with both proximal and distal arm segments being controlled primarily at the shoulder. In comparison, hand path trajectories produced by the non-dominant limb were laterally curved and had greater overall curvatures. This was associated with increased shoulder excursion and inefficient use of intersegmental interaction torques. Subsequent studies by Sainburg and colleagues (Bagesteiro et al., 2002; Sainburg, 2002; Wang et al., 2003, 2004) provided strong evidence in support of a dominant arm advantage in the specification and control of arm trajectory.

A role of the non-dominant arm system has been suggested in spatially orienting a body segment posture. Bagesteiro et al. (2002) assessed inter-limb differences in load compensation. In this study, participants' limbs were constrained to a horizontal plane. They were asked to perform aiming movements to a target position of 20° of elbow flexion. At random times, a 2 kg mass was suspended 20 cm lateral to the forearm without warning to the participant. They found that when the load was suddenly introduced, the non-dominant limb was able to achieve a level of endpoint accuracy similar to that exhibited in the non-load condition. The dominant limb, on the other hand, showed consistent overshooting of the target. Bagesteiro et al. concluded that the non-dominant arm is specialized in sensory feedback-mediated error correction (2002). Subsequent studies (Sainburg, 2002; Wang et al., 2003; Bagesteiro et al., 2005) found additional support for this part of the theory.

While these studies provide insight into the specialized control of dominant and non-dominant limb movements, very little research has been dedicated to addressing the differences between the limbs during the performance of complex, multiplanar tasks, such as ADL performance. It is of fundamental importance, therefore, to investigate and quantify manual asymmetries kinematically during the performance of activities of daily living.

2.3. Effects of aging on tool use

2.3.1. Effects of aging on tool acquisition (Reach-to-grasp)

It has been well established that aging contributes to the slowing of motor processes and performance. Most common characteristics of aging are stooped posture (Woodhull-McNeal, 1992), shuffling gait (Tinetti et al., 1988) and slowed and hesitant movement (Tinetti et al., 1988). Research suggests that the decline or compensation strategies in upper limb motor control seen in aging arise from widespread neuromuscular and sensorimotor changes, such as loss of proprioceptive and cutaneous sensibility (Evans, 2010) or voluntary muscle strength. Aging is also associated with loss of neurons and synapses, which slow conduction velocity and potentially change neural network connectivity (Fjell et al., 2010).

Motor processes involved in the performance of reach-to-grasp movements are sensitive to aging. Performance of activities of daily living becomes slower in older adults due to a reduction in central processing capabilities (Welford, 1985). Some suggest that this inefficient control in motor responses arises because older adults operate as a closed-loop system (Roy et al., 1996), meaning that older adults tend to rely more on perception to continuously and consciously adjust muscle movements. Rabbitt (1982) suggests that older adults' utilization of feed-forward control declines and therefore, they must rely solely on feedback control. However, a number of kinematic studies have shown that the increased movement time in older adults is a direct consequence of longer time spent in deceleration phase of movement and smaller peak velocities (Darling et al., 1989; Haaland et al., 1993; Roy et al., 1993). It is suggested that this is due to more time needed to process feedback information, as well as possibly a reflection of reduced force generation at movement initiation (Roy et al., 1996). Movement duration and time in deceleration are longer in older adults (Bennett et al., 1994). In fact, movements in older adults slow down by as much as 15-30% (Diggles-Buckles, 1993). Deceleration time in older adults is approximately 60% of movement time, compared to younger adults who dedicate only 56% to deceleration phase of movement (Bennett et al., 1994). This prolonged time in deceleration is due to proportionally earlier occurrence of PV.

The focus of a number of studies in motor control has been on simple reaching movements. Brown et al. (1990) asked participants to perform visually guided flexion/extension arm movements. In contrast to temporally symmetric and highly reproducible movements quantified in younger adult group, older adults were more variable particularly during the deceleratory phase of reaching movement. Further, older adults were unable to stop smoothly and made corrective movements as they approached the target. Longer time spent in the approaching (decelaration) phase is related to the accuracy requirements of the task – the smaller the target, the more time is spent in approaching phase. As individuals age, visual acuity and proprioceptive accuracy decline

(Kokmen et al., 1978) forcing older adults to recruit corrective mechanisms as they reach for an object. This in turn prolongs the deceleratory phase of movement during reaching. Further, more variable movement in older adults is also frequently observed (Bennett et al., 1994). Darling et al. (1987) analyzed variability in trajectory of movement in 10 millisecond time increments in both single and multi-joint arm movements in younger and older adults. They discovered that in young participants, trajectory variability is larger during the acceleratory phase, but decreases during deceleratory phase. In contrast, in older adults, trajectory variability was high in both phases of movement. Older adults also exhibit compensation strategies in coordination of bimanual and multi-joint movements. For example, when required to move elbow and shoulder simultaneously, their movements are slower and less smooth as opposed to performing single joint actions (Seidler et al., 2002). Bennett et al. (1994) have found only subtle differences between younger and older adults in reaching movements. In their study of older and younger adults, they asked participants to reach and grasp a cylinder in front of them. They found that the movement duration is longer for older participants. Peak acceleration and deceleration amplitudes of the arm that was reaching were lower in the older adult group. Further, younger adults devoted approximately 56% of their time to deceleration phase of movement relative to older adults who spent 60% of their total movement time in deceleration phase (Bennett et al., 1994). It can be noted that very little research to date has focused on the effects of aging on tool use phase of movement and in particular, on the effect of aging on manual asymmetries while manipulating a tool.

2.4. Interplay of aging, manual asymmetries and task conditions

2.4.1. Effects of aging on manual asymmetries

Manual asymmetries in motor tasks may be sensitive to aging. Physiological and anatomical changes in asymmetry have recently been investigated. Fjell et al. (2010) have shown that there exists a volumetric brain reduction in healthy older adults, which in turn may be responsible for change in organization of neuroanatomical networks. Neuroanatomical network changes may be due to shrinkage of neurons, reductions in synaptic spines, lower number of synapses, as well as significant reductions in the length of myelinated axons (up to 50%) (Fjell et al., 2010). It has been shown that brain white matter integrity declines as a result of aging (Sullivan et al., 2006), as well as gray matter (Fjell et al., 2009). Together, these changes contribute to reduced processing speed, increased performance variability, and general cognitive decline (Hedden et al., 2004). As the ratio of gray matter to white matter is greater in the left hemisphere (Gur et al., 1980), it could be that the age-related decline in gray matter is faster relative in the right-hemisphere. Hence, these changes may play a role in reductions of cognitive and motor performance asymmetries.

Currently, there exist two models of hemispheric asymmetry associated with aging: the hemispheric-asymmetry reduction model (HAROLD) and the right hemisphere-aging model. HAROLD model states that prefrontal cortex (PFC) activity tends to be less lateralized in older adults in comparison to younger adults under similar conditions (Cabeza, 2002). Thus, as individuals age, contralateral circuits which are important for sensorimotor control, deteriorate, requiring compensatory recruitment of ipsilateral circuits instead (Przybyla et al., 2011). Cognitive tasks, for example, elicit bilateral activations in older adults relative to younger adults (Cabeza et al., 2004; Bergerbest et al., 2009). If these findings were to be applied to motor performance, an overall reduction in manual asymmetries would be observed between the two limbs as a function of age. This reduction in motor asymmetry in older adults has been reported during the performance of horizontal plane reaches (Przybyla et al. 2011), peg moving (Francis et al., 2000) and transfer of movement information across arms (Wang et al., 2011). Przybyla et al., for example, found that the non-dominant arm of older adults has straighter and more accurate movements when horizontally reaching relative to younger adults (2011). Hence, the non-dominant arm produced movements similar to that of the dominant arm in older adults as opposed to younger adults. However, the speed of movement was controlled in this experiment as the researchers required the participants to move at a certain speed, and thus, the symmetrical performance of both arms may have been a direct result of this. Further, Przybyla et al. (2011) did not report the degree of handedness in their younger and older adults groups. It could be that they had a sample of individuals whose degree of right-handedness was not strong. To expand on these findings, Raw et al. (2012) asked a group of younger and older adults to trace a line of different thickness as quickly as possible. Their findings supported the view of Przybyla et al. (2011), as they found that the younger adult group had larger manual asymmetries relative to their older adult group with respect to movement time and shape accuracy. Further, Weis et al. (1991) have found that the corpus callosum decreases in size in older adults. Since corpus callosum links the two cerebral hemispheres, this degradation may lead to temporal increase in inter-hemispheric communication (Jeeves et al., 1996). Consequently, this increase in communication between cerebral hemispheres would lead to a reduction in inhibitory callosal interactions and thus, global reduction of manual asymmetries due to aging.

The right hemisphere-aging model suggests that age-related cognitive declines affect functions located in the right hemisphere to a greater degree than those functions associated with the left hemisphere (Dolcos et al., 2002). Support for this model has been found during the performance of simpler motor tasks. Weller et al. (1985) investigated whether increasing age would preserve the dominant hand motor skills more relative to the non-dominant hand in a pegboard task. They found that both the dominant and non-dominant hand performance decreased with age. However, their findings also included evidence that the abilities associated with the right hemisphere were more affected by aging process relative to those located in the left-hemisphere. Thus, the non-dominant arm (right-hemisphere) performance declined more than that of the dominant arm (left-hemisphere). Age-related decline in motor tasks is due mostly to deterioration of central nervous processes, such as neuronal fall-out and diffuse cortical atrophy, within some regions of the right hemisphere (Gerhardstein et al., 1998). Since performance of different motor tasks is associated with different right hemisphere regions, it could be that the age-related decrease in manual asymmetries only affects some motor tasks.

Although there is some evidence for the models described above, research to date is not conclusive. Teixeira et al. (2000), for example, have found that tasks such as repetitive tapping and drawing, elicit manual asymmetries across all ages (18 to 63). In the finger-tapping task, consistent manual asymmetries characterized by tapping time were quantified across all ages. The non-dominant arm was consistently slower at tapping 30 times in a row as fast as possible. However, in the drawing task, which required participant to draw a sequence of 10 circles in a row, greater manual asymmetry was found in older adults. The dominant hand had faster drawing time than non-dominant hand in individuals over the age of 60 relative to younger adult groups. Increase in manual asymmetries in the drawing task could be due to greater age-related decline in the right hemisphere processing functions, such as the motor control of the non-dominant limb and is consistent with the previous findings (Francis et al., 2000). In addition, Francis et al. (2000) found that manual asymmetries persist in older adults when finger tapping, tracing triangles, performing steadiness tester, as well as Minnesota rate of manipulation task (ie. tests manual dexterity). Thus, it appears as though the degree of manual asymmetry appearance in younger and older adults may be dependent on the specific tasks performed. Therefore, more research is required to determine if reduction in some tasks, but increase in manual asymmetries during the performance of other tasks in older adults is task specific, a part of a compensation mechanism or a question of age-related decline (Rowe et al., 2006).

2.4.2. Interplay of task conditions and manual asymmetries in healthy controls

Manual asymmetries in the context of different task conditions during the performance of different ADLs in healthy young controls have only been investigated in one study to date. Heath et al. (2002) evaluated the performance of “slicing bread” gesture with both limbs in ten neurologically intact males. They evaluated movement time, peak velocity and time after peak velocity within each cycle of movement. Overall, they found that there were no differences between dominant and non-dominant arms in terms of movement time, peak velocity, or time after peak velocity. Although no differences between the limbs were quantified for temporal aspects of movement, differences between the limbs were found in terms of spatial aspects of movement, such as the trajectory shape and plane of movement. Further, there was an effect of task condition on peak velocity. During pantomime condition, higher peak velocities were achieved in both limbs relative to tool condition. This study gave some insight into the presence of manual asymmetries in different task conditions and spatial as opposed to temporal measures. However, due to the small sample size and inclusion of only younger adults in this study, it is uncertain whether this would be the case if manual asymmetry in different task conditions were examined in the context of aging. Left-hemisphere stroke and hence, limb apraxia most often affects individuals over the age of 50. Hence, it is of importance to expand this research onto the aging population and examine interplay between manual asymmetries and different task conditions in older adults.

3.0 Hypotheses

General Hypothesis

There will be a reduction in manual asymmetries in older adults relative to younger adults.

3.1. Effects of manual asymmetries

Temporal Aspects

There will be a right hand advantage with right hand spending more time during time to peak velocity, less time in time after peak velocity and have higher peak velocity than left hand. This will be quantified in both ADLs.

Euler Angles (Please refer to Methods for description of Euler Angles)

Left hand will have higher range of joint angles at the wrist, elbow and shoulder in both ADLs.

Joint Coordination

Right hand will have higher inter-joint synchrony (as defined by coefficient of correlation of angle-angle, velocity-angle and velocity-velocity relationships) relative to the left hand. This will be the case in both ADLs.

3.2. Effects of Aging

Temporal Aspects

Older adults will spend more time in time to peak velocity, more time in time after peak velocity and have lower peak wrist velocity relative to younger adults.

Euler Angles

Older adults will produce a lower average range of joint angles at the wrist, elbow and shoulder in both ADLs relative to younger adults.

Joint Coordination

Older adults will have lower inter-joint synchrony (correlation coefficients for angle-angle, velocity-angle and velocity-velocity relationships) than younger adults.

3.3. Effects of Task Condition

Temporal Aspects

Pantomime condition will exhibit less time to peak velocity, more time after peak velocity and higher peak velocities relative to the tool condition.

Euler Angles

Pantomime condition will produce higher average range of joint angles at the wrist, elbow and shoulder than tool condition.

Joint Coordination

Tool condition will have higher inter-joint synchrony (correlation coefficients) when than pantomime condition.

3.4. Effects of age on manual asymmetries

Temporal Aspects and Euler Angles

There will be a reduction in manual asymmetries in older adults relative to younger adults in both ADLs, with respect to PV, TPV, TAPV, CD and wrist/elbow/shoulder joint angles.

Joint Coordination

Older adults will have lower inter-joint synchrony (coefficient of correlation) in left hand relative to right hand and younger adults.

3.5. Effects of task demands on manual asymmetries

Temporal Aspects

Pantomime condition will increase peak velocity, time to peak velocity and time after peak velocity in the left hand relative to tool condition and right hand.

Euler Angles

Pantomime condition will increase the average range of joint angles at the wrist, elbow and shoulder in the left hand relative to tool condition and right hand.

Joint Coordination

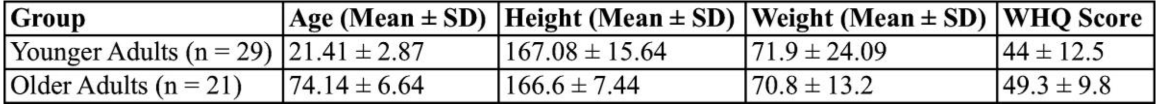
Pantomime condition in left hand will have lower inter-joint synchrony (coefficient of correlation) relative to right hand and tool condition.

4.0 Methods

4.1. Participants

Fifty healthy, right-hand dominant adults were recruited to participate in this study. Two groups comprised of twenty-nine young, healthy adults between 18-30 years of age (17 F; 12 M) and twenty-one healthy, community-dwelling, older adults over the age of 65 (12 F; 9 M). Basic demographics can be found in Table 1 (further details available in Appendix B).

Table 1: Study Participant Demographics



Group	**Age (Mean ± SD)**	**Height (Mean ± SD)**	**Weight (Mean ± SD)**	**WHQ Score**
Younger Adults (n = 29)	21.41 ± 2.87	167.08 ± 15.64	71.9 ± 24.09	44 ± 12.5
Older Adults (n = 21)	74.14 ± 6.64	166.6 ± 7.44	70.8 ± 13.2	49.3 ± 9.8

Younger adults were recruited using posters and verbally through word-of-mouth. Older adults were recruited from the community using Waterloo Research and Aging Pool database. Participant exclusion criteria included:

- left-hand dominant
- neurological or physiological disease/disorder of the upper limb (ex. Stroke or carpal tunnel syndrome)
- history of concussion or brain trauma in the past 6 months
- upper limb or lower back injury within the past 6 months
- blindness or visual problems that cannot be corrected for
- shoulder surgery or endoprosthesis

The purposes, methods, risks and benefits of the study were explained to the participants. Participants provided informed consent form prior to participation. They were also asked for their weight, height and age. Every participant was assigned a unique code attached to his or her initials. Older adults were remunerated $20 for their participation in the study, while younger adults were not given any remuneration for their participation. Participants received a feedback letter after participation including researcher contact information and study details.

4.2. Photographs and Video Recording

Photographs were taken during the study, if the participants provided consent. The photographs focused on upper limb and trunk of the participant. Any facial features or other distinguishing features that were visible in either of the photos or the videos were obscured to maintain participant confidentiality. Photoshop was used to blur the facial or other distinguishing features after the photos have been recorded. These photos may be helpful when giving scientific presentations or in archival publication.

4.3. Waterloo-Handedness Questionnaire

After signing the consent form (Appendix A) and completing the medical questionnaire (Appendix C), participants in both age groups were asked to complete a version of the Waterloo Handedness Questionnaire (Steenhuis et al., 1990) (see Appendix D). This questionnaire asked individuals to indicate their preferred hand in the performance of a variety of unimanual tasks (e.g. writing, holding a toothbrush, picking up a jar). The questionnaire contained five possible responses, “left always (-2),” “left usually (-1),” “both hands equally (0),” “right usually (+1),” and “right always (+2)”. Individual responses were scored and then summed to obtain a mean composite score. Since this study included only right-handers, mean scores were expected to be above 0 on the questionnaire. Scores on the Waterloo Handedness Questionnaire were used to examine the relationship between the performance measures (Grooved Pegboard and kinematic variables) and this hand preference measure.

4.4. Grooved Pegboard

After completing the Waterloo-Handedness Questionnaire, participants were asked to complete the Grooved Pegboard task, which is a unimanual task, used to examine motor performance. The standard grooved pegboard apparatus (Lafayette instruments # 32025) was used to complete this part of the study. The apparatus consisted of a metal surface (10.1 cm x 10.1 cm), with a matrix (5 by 5) of keyhole-shaped holes in variety of orientations. Pegs were placed in a receptacle and were approximately 3 mm in diameter and had a small key-like ridge alongside them that was approximately 2.5 cm in length.

4.1.1. Grooved Pegboard procedure

A standard procedure for completing the Grooved Pegboard Test was utilized. Participants were seated directly in front of the pegboard and were instructed to place, one at a time, 25 pegs into the holes as quickly as possible. They started with their dominant hand. Since this was their right hand, the order of peg placement from the receptacle to the board was from left to right, beginning with the top row. They always started filling the next row from the left side of the metal surface. When they used their left hand, they completed the task in reverse (ie. from their right to left). The stopwatch started when the participant lifted the first peg from the receptacle. The stopwatch was stopped when the last peg was placed in the last hole. Participants were also timed on their speed for removing the pegs one at a time and placing them back into the receptacle in the reverse order.

The number of errors in the performance was also recorded. An error was seen when a participant picked up a peg and dropped it when moving it from receptacle to the hole or when placing a peg into the hole. Participants performed both tasks (place and replace) three times with each of the hands. The order of hands was not randomized between participants. For full summary of pegboard data, please see Appendix E.

5.0 Instrumentation

All upper limb and trunk movements were tracked using an optoelectronic passive motion tracking system Vicon MX20+ (Vicon Motion Systems, Oxford, UK). Eight cameras were positioned around the collection space to capture the collection volume. The cameras recorded the global positions of reflective markers adhered to skin on bilateral sides of the body overlaying the anatomical landmarks of the thorax, shoulder blade, spine, upper arm, forearm, hand, thumb and index fingers (Table 2). The position of each of the segments was sampled at 60 Hz.

Table 2: Anatomical landmark locations for marker set-up.

Segment	Marker	Location
Thorax	STE	Suprasternal Notch
	XIP	Xiphoid Process
	C7	Spinous process of the 7th cervical vertebra
	T8	Spinous process of the 8th thoracic vertebra
	T12	Spinous process of the 12th thoracic vertebra
	L5	Spinous process of the 5th lumbar vertebra
Shoulder	AR	Acromion
Arm	MEC	Medial epicondyle
	LEC	Lateral epicondyle
	RP	Radial styloid process
	UP	Ulnar styloid process
Hand	SC	Scaphoid bone
	PI	Pisiform bone
	MP5	5th metacarpal phalangeal joint
	MP2	2nd metacarpal phalangeal joint
Digits	TP1	Thumb proximal phalange 1
	TP2	Thumb proximal phalange 2
	TD1	Thumb distal phalange 1
	TD2	Thumb distal phalange 2
	IP1	Index proximal phalange 1
	IP2	Index proximal phalange 2
	IM1	Index middle phalange 1
	IM2	Index middle phalange 2
	ID1	Index distal phalange 1

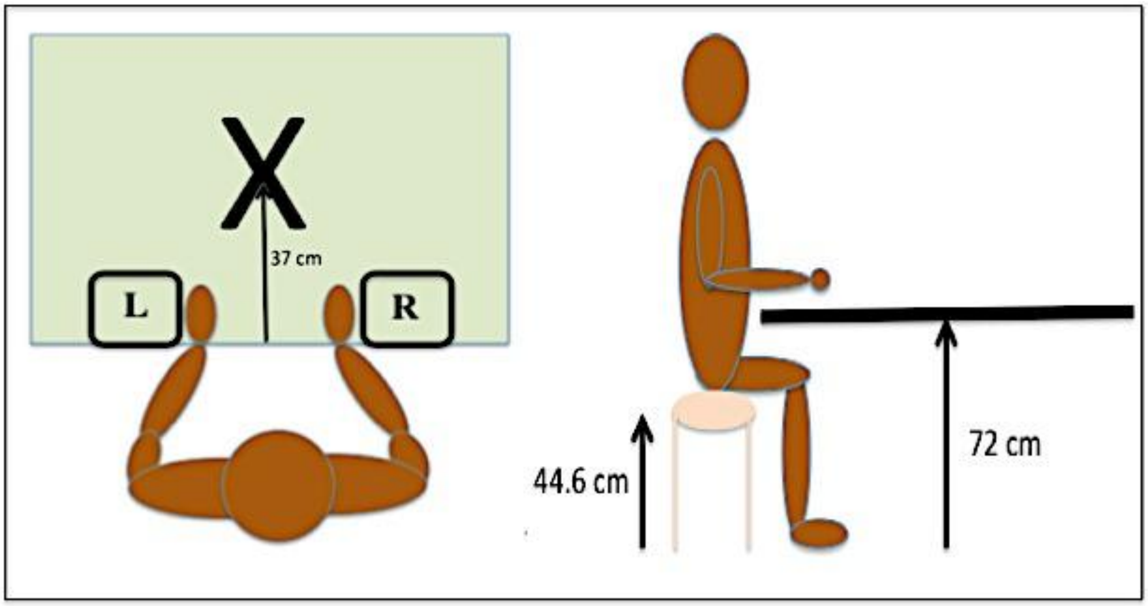


Figure 3: Experimental set-up for capturing upper limb movements during the performance of activities of daily living (superior and side views).

5.1. Experimental procedures

Once the reflective markers were attached to their respective anatomical landmarks, the participants sat comfortably on a wooden stool (44.6cm high) in front of a 72 cm high table in the center of the collection space (Figure 3). A 4 second calibration trial was recorded with the participant seated in the collection space with an approximately 90° of elbow flexion.

The experimental and participant set-up was constrained to some degree. The participant's hand was positioned at either the letter "R" or "L" (see Figure 3). An "R" letter denoted the position of the dominant arm, while the "L" letter was symbolic for the non-dominant arm position. The midline of the table was marked with an "X" with a black masking tape. This symbol represented the location of an actual or imaginary tool prior to grasping it. The participant was encouraged to move at a self-defined comfortable pace.

5.2. Activities of daily living

Two ADLs were chosen from the Waterloo-Sunnybrook Apraxia Battery to be performed in this study: drinking from a cup and slicing a loaf of bread with a knife. Drinking from a cup was chosen because it represents a task that is non-cyclical in nature (ie. it does not require repetitive movements to complete the task). On the other hand, ‘slicing bread’ gesture was chosen because it represents a learned, skilled movement, which requires a number of repetitive cycles (ie forward and backward movements of the limb) to successfully complete the task. These cycles are characterized with sharp reversals in direction, as well as overlapping planes of movement (Clark et al., 1994). When this gesture is performed correctly, it requires precise coordination of multiple joints (shoulder, elbow and wrist) to produce spatio-temporally appropriate hand trajectories (Poizner et al., 1995). Performance of both of these gestures because they are learned skills is predisposed to being more severely affected in patients with apraxia (Clark et al., 1994).

5.3. Task Conditions

Two conditions were collected: pantomime and tool. The pantomime condition required a participant to imagine a tool in front of them (located on the X), reach for it, grasp it, use it, put it back on the “X” and return to a neutral position. In the tool condition, the tool was placed in front of the participant on the “X” and they were asked to reach for it, grasp it, pretend to use it, put it back on the “X” and go back to the neutral position. “Knife” gesture required a participant to perform nine repetitive back-and-forth movements until the investigator told them to stop. One back-and-forth movement was considered a repetition and therefore, one cycle. Both, the knife and the cup ADL was performed six times.

5.4. Randomization procedure for limbs, task conditions and activities of daily living

The experimental protocol was block randomized between hands and conditions. Since the markers were adhered to skin bilaterally prior to the beginning of the experimental procedure, the performance of ADLs was randomized between hands (e.g. first ADL performed with right hand; second ADL performed was with left hand). Further, if participant A started the experimental procedure with right hand, participant B started the experimental procedure with left hand. Conditions were counterbalanced. Two ADLs were analyzed separately.

6.0 Data Analysis

6.1. Waterloo Handedness Questionnaire Score

Individual responses on the WHQ questionnaire were scored and then summed to obtain a mean composite score. Since this study included only right-handers, it was expected to obtain mean scores above 0.

6.2. Grooved Pegboard data analysis

Time in seconds was recorded during the pegboard task for both hands in younger and older adults. Mean movement time in seconds was found for the three trials performed for each hand and participant.

6.3. Laterality Quotient: Grooved Pegboard and WHQ Correlations

To be able to compare the Waterloo Handedness Questionnaire and the Grooved Pegboard Test, the scores from the Grooved Pegboard Test were converted into a laterality quotient. Laterality quotient was calculated by taking the difference between the dominant and non-dominant hands as a function of overall movement time of the two hands (NH – DH/DH+NH), and multiplying the result by 100. In terms of interpretation of the results in this case, the magnitude of the laterality quotient reflects the size of the performance differences between the hands, while the direction of the quotient reflects which hand has the advantage (- reflects a non-dominant hand advantage). Correlations were performed between the composite scores on the Waterloo-Handedness

Questionnaire and performance on both the place and remove tasks of the Grooved Pegboard Test separately for younger and older adults.

6.4. Kinematic variables in analysis of upper limb movements: An Overview

The analysis focused on the use phase of the movement for both ADLs. Several dependent measures were assessed in both hands and conditions:

1. Temporal aspects of movement: peak velocity (PV), time to peak velocity (TPV), time after peak velocity (TAPV), and cycle duration (CD) of the wrist joint
2. Mean range of motion for shoulder, elbow and wrist joints
3. Angle-angle, velocity-angle and velocity-velocity relationships of shoulder, elbow and wrist joints. In particular, the relationship between elbow flexion/extension and upper arm elevation; the relationship between elbow flexion/extension and linear wrist velocity; the relationship between upper arm yaw and elbow flexion/extension; and the relationship between elbow and wrist linear velocity were examined

6.5. Data Analysis of Kinematic Variables

Marker data provided position data of the upper limbs and the thorax in the global coordinate system. All motion tracking data was low-pass filtered with a 2^{nd} order dual-pass Butterworth filter with a cut-off frequency of 4 Hz.

Custom-made software written by TL in MATLAB 7.9.0 R2011B (Mathworks, Natick, MA) was used for data analysis. The local coordinate system of the thorax was constructed according to the International Society of Biomechanics (ISB) definition (Wu et al., 2005). The thorax coordinate system was defined as the reference coordinate system for the orientation of upper limb segments. In order to transfer the global system of marker data into the thorax local coordinate system, a rotation matrix was calculated using unit vector of the thorax global coordinate system according to the ISB definition. The sternal notch was defined as the thorax origin. From there, the sternal notch global system marker data was subtracted from all of the global system marker data (translation into the thorax system) and then multiplied by the new, local thorax coordinate system (rotation matrix). New local coordinate system of the humerus, forearm, and hand was then constructed according to the ISB definition (Wu et al., 2005).

Once the data was placed into the thorax local coordinate system, positions of the markers were differentiated using a finite difference method to yield linear velocity (1) of the shoulder, elbow, wrist, and hand.

$$v\ (t) = \frac{dx\ (t)}{dt} = \frac{x\ (t) - x\ (t-1)}{\Delta t}, \tag{2}$$

where v is velocity; t is time; x (t) is current displacement point; x (t-1) is previous displacement point; Δt is t_2-t_1.

The data were divided into three different phases of movement based on linear velocity: reach, use, and termination of movement phase (Figures 4 and 5). To isolate the use phase of movement, the reach phase was defined as the time from initiation of movement from a resting pose to grasping of the tool. The use phase was defined as the grasping of the tool and its manipulation (Arbib et al., 2009) until it was placed back on the “X”. Termination and reach phases were not analyzed in detail.

6.5.1. Defining Use Phase in Cup and Knife ADL

The use phase of movement was defined as the time the tool was grasped and manipulated until it was put down. Mathematically, it was defined as a difference between a minimum and next maximum velocity value in the primary axis of movement that exceeds the amplitude limit of 2% of maximum velocity (Murphy et al., 2011). In the cup ADL, the primary axis of movement, defined as the axis in which highest PV was achieved, was Y axis (superior/inferior). Use phase in cup ADL was divided into towards the body movement (moving the cup towards the mouth) and away from the body movement (moving the cup away from the body). For the knife ADL, the axis achieving the highest PV was the X axis (forward/backward). Thus, use phase of movement was defined based on this axis and involved nine cyclical movements. First and last local maximum and minimum in the knife ADL were dismissed to reduce starting effects and anticipation of the movement end (Hermsdorfer et al., 2011).

6.5.2. Temporal analysis of movements in use phase

After the curve was divided into 3 phases of movement (see above), the use phase was isolated to calculate temporal aspects of movement. For the knife ADL (Figure

4), one cycle of movement was defined as one forward and one backward movement of the wrist. For the cup ADL (Figure 5), movement towards the mouth and away from the body (placement of cup back on the table) represented two cycles. PV, TPV, TAPV and CD were based on the wrist joint. PV of one cycle of the use phase was determined by taking the maximum and minimum values on the velocity curve. For the knife ADL, this included a total of fourteen PVs within a trial. The cup ADL consisted of two PVs within a trial (one PV for each, towards and away from body movement). TPV was defined as the time from the beginning of the movement to the attainment of maximum (positive) PV for knife ADL. In cup ADL, TPV was defined as the time from the beginning of movement to the PV (negative for towards the body; positive for away from body). TAPV for knife ADL was the time from attainment of peak (positive) velocity to the next peak velocity (in this case, negative peak velocity). In cup ADL, TAPV was defined as the time it took to decelerate a movement from either a positive or a negative PV. CD was defined as the total time it took to perform one cycle of movement for both cup and knife ADL. This was done for each trial in each condition.

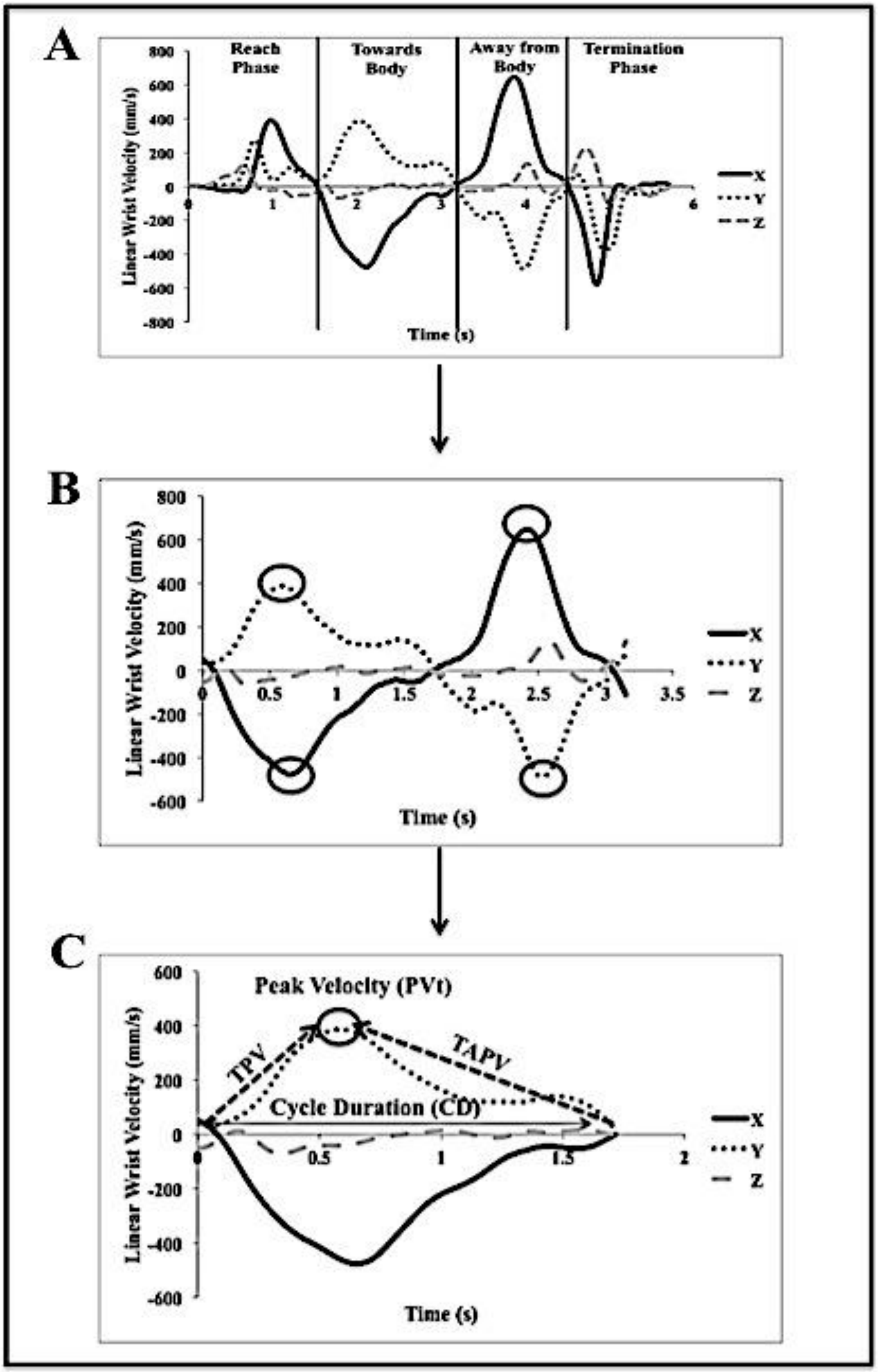
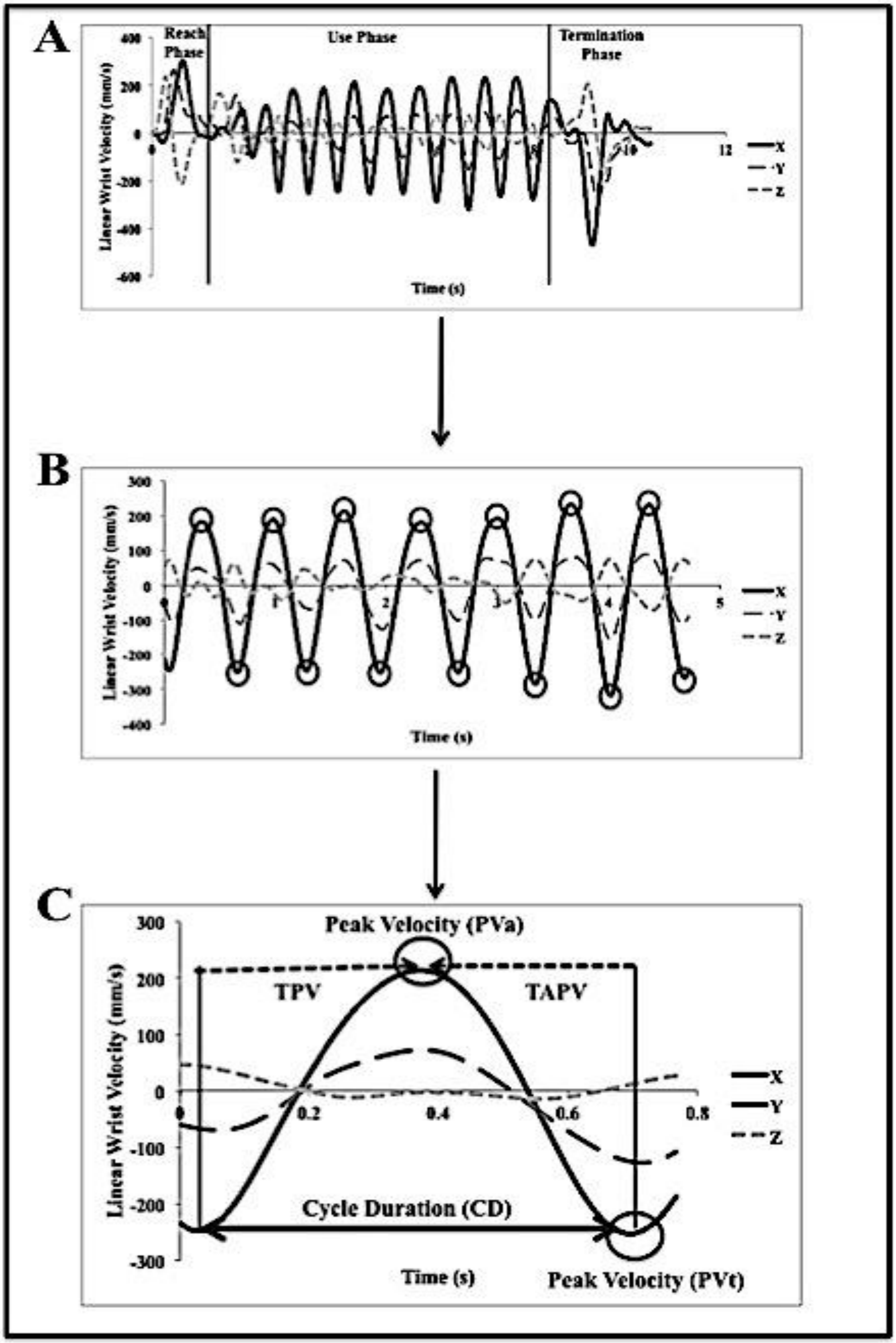

A
Reach Phase
Towards Body
Away from Body
Termination Phase
Linear Wrist Velocity (mm/s)
800
600
400
200
0
-200
-400
-600
-800
0
1
2
3
4
6
Time (s)
X
Y
Z
B
Linear Wrist Velocity (mm/s)
800
600
400
200
0
-200
-400
-600
0
0.5
1
1.5
2
2.5
3
3.5
Time (s)
X
Y
Z
C
Peak Velocity (PVt)
TPV
TAPV
Cycle Duration (CD)
Linear Wrist Velocity (mm/s)
600
400
200
0
-200
-400
-600
0
0.5
1
1.5
2
Time (s)
X
Y
Z

Figure 4: Representation of the linear wrist velocity for cup ADL and calculation of dependent measures. X axis depicts movements forward/backward; Y axis depicts superior/inferior movement (up/down); Z axis depicts lateral/medial movement (right/left). A. Linear wrist velocity is divided into reach, towards body, away from body and termination phases. B. Use phase of movement for cup ADL. Two cycles can be seen in this figure. Circles depict peak velocities. C. Example of a towards the body cycle for cup ADL. TPV is time to peak velocity; TAPV is time after peak velocity; PVt is peak velocity up towards the mouth; CD is cycle duration.



A
Reach Phase
Use Phase
Termination Phase
Linear Wrist Velocity (mm/s)
400
200
0
-200
-400
-600
0
8
10
12
Time (s)
X
Y
Z
B
Linear Wrist Velocity (mm/s)
300
200
100
0
-100
-200
-300
-400
1
2
3
4
5
Time (s)
X
Y
Z
C
Peak Velocity (PVa)
TPV
TAPV
Linear Wrist Velocity (mm/s)
300
200
100
0
-100
-200
-300
0
0.2
0.4
0.6
0.8
Cycle Duration (CD)
Time (s)
Peak Velocity (PVt)
X
Y
Z

Figure 5: Representation of the linear wrist velocity for knife ADL and calculation of dependent measures. X axis depicts movements forward/backward; Y axis depicts superior/inferior movement (up/down); Z axis depicts lateral/medial movement (right/left). A. Linear wrist velocity is divided into reach, use and termination phases. B. Use phase of movement for knife ADL. Seven cycles can be seen in this figure. Circles depict peak velocities. C. Example of one cycle for knife ADL. TPV is time to peak velocity; TAPV is time after peak velocity; PVa is peak velocity away from body; PVt is peak velocity up towards the body; CD is cycle duration.

6.5.3. Reduction of temporal data for statistical analysis

For statistical analysis, mean values within a trial were calculated. Values obtained for PV, TPV, TAPV, and CD within a trial were averaged for each of the dependent measures to obtain a mean value for that trial. Since, the experimental protocol consisted of six trials for the knife and the cup ADL for each participant, mean values obtained within a trial were then averaged across the six trials. These were then subjected to statistical analyses.

6.5.3.1. Cup

The cup ADL was divided into towards body and away from body movement. Two PVs, TPVs, TAPVs and CDs were quantified for one trial. Six trials for one participant were averaged giving one mean value per participant for hand and condition. Towards and away from body movements were treated separately.

6.5.3.2. Knife

Mean of six trials was calculated for knife ADL. One trial in the knife ADL yielded seven values for forward movement and seven values for backward movement for PV, TPV, TAPV and CD. These values were averaged to give one mean value per trial. After this, six trials were averaged to yield one mean value per participant for hand and condition. Forward and backward movement were treated separately.

6.5.4. Euler angles

Euler angles were calculated according to the International Society of Biomechanics Standards (Wu et al., 2005). In the following section, sequence of rotations is defined. This is also provided in detail in International Society of Biomechanics guidelines (Wu et al., 2005).

Glenohumeral (GH) joint (Y-X-Y)

The sequence of three rotations for the glenohumeral joint (Figure 6) is:

1. Plane of elevation as defined by 0° abduction or 90° of forward flexion, coincident with the Y-axis of the thorax coordinate system.
2. Axial rotation as defined by internal rotation (positive) and external rotation (negative), coincidental with Y-axis of the humeral coordinate system.
3. Elevation (negative) coincidental with X-axis of the humerus coordinate system.

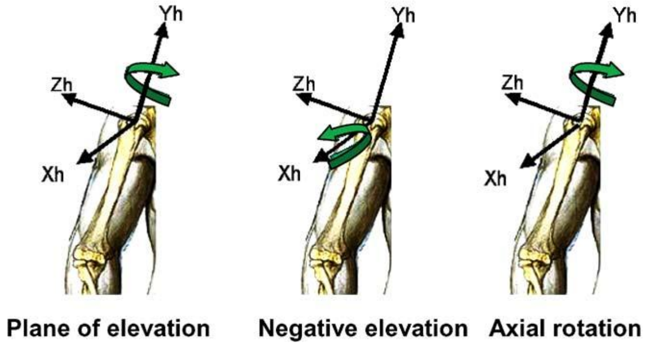


Figure 6: Glenohumeral joint coordinate system (Wu et al., 2005).

Elbow joint (Z-X-Y)

The sequence of three rotations for the elbow joint is:

1. Flexion (positive) or extension (negative) coincidental with the Z-axis of the humeral coordinate system
2. Axial rotation of the forearm (pronation/supination) coincidental with the Y-axis of the forearm coordinate system
3. Carrying angle, coincidental with the rotated X-axis of the forearm coordinate system

Wrist joint (Z-X-Y)

The sequence of three rotations for the wrist joint is:

1. Flexion/extension coincidental with the Z-axis of the proximal segment coordinate system

2. Pronation/supination coincidental with the Y-axis of the distal segment coordinate system
3. Radial/ulnar deviation coincidental with the axis perpendicular to the 1 and 2 above

Once the Euler angles for wrist, elbow and shoulder were calculated, the range of motion for the whole cup use movement and each cycle within a knife ADL for each of the joints was obtained.

6.5.5. Laterality Quotient and Kinematic Data

Laterality quotient was calculated for each temporal variable and mean range of Euler angles. First, the mean was calculated for each participant. Cumulative total was then calculated using:

$$CT = LH + RH,$$

where CT is cumulative score, LH is mean PV/TPV/TAPV for left hand and RH is mean PV/TPV/TAPV for right hand.

Difference between the two hands was then calculated using:

$$D = RH – LH,$$

to give a result measure, also known as laterality quotient:

$$R = \left(\frac{D}{CT}\right) \times 100$$

6.5.6. Relationships between spatial and temporal aspects of movement

Angle-angle, angle-velocity and velocity-velocity data for the use phase were plotted on graphs after which they were subjected to statistical analyses. For the knife ADL, angle-angle relationships examined were upper arm elevation and elbow flexion/extension; angle-velocity relationships examined were linear wrist velocity and elbow flexion/extension; velocity-velocity relationships examined were linear wrist velocity and linear elbow velocity. This was done for both, pantomime and tool condition, as well as dominant and nondominant limb. Once the plots of upper arm elevation and elbow flexion/extension and linear wrist velocity and linear elbow velocity were obtained, due to its linear nature, a correlation coefficient was calculated for every trial within a participant for linear elbow velocity and linear wrist velocity, as well as upper arm elevation and elbow flexion/extension. This correlation coefficient was then transformed into a Z-score. Mean Z-score of all six trials for each participant, hand and condition was calculated. Z-scores were then subjected to statistical analyses.

The relationship between elbow flexion/extension and linear wrist velocity was parabolic. To quantify the relationship between elbow flexion/extension and linear wrist velocity, a best fitted ellipse was calculated and fitted to the seven cycles within a trial. When ellipse was fitted, a root mean square error (RMSE) was calculated from the best fitted ellipse, as a means of describing variability in movement. The higher the RMSE in this case, the lower the interjoint synchrony and the higher the variability within the trial. Further, the shape of the ellipse was also calculated by taking the amount of movement in the X direction and dividing it by amount of movement in the Y direction. In this case, a larger ratio would denote higher wrist velocity and less elbow flexion/extension, while a smaller ratio would describe the opposite relationship.

In the cup condition, angle-angle relationships examined were elbow flexion/extension and upper arm elevation; velocity-angle relationships examined were linear wrist velocity and elbow flexion/extension, as well as linear elbow velocity and upper arm elevation.

7.0 Statistical Analysis

Statistical analyses were performed using JMP 10 (SAS Institute Inc., North Carolina, USA).

7.1. Grooved Pegboard analysis

A hand (dominant hand, non-dominant hand) by age (young, old) by sex (male, female) mixed measures ANOVA was performed for place and remove tests of the Grooved Pegboard test. Given the greater variability in the older adult data in the place task a Levene's homogeneity of variance test was performed on the place and remove tasks of the pegboard. The remove task passed the test, but there was heterogeneity of variance in the place task [Place right: F(3,44) = 7.059, p = .001; Place left: F(3,44) = 6.038, p = .002]. Considering the relative comparability in the cell sizes and the normal distribution of the data, the mixed measures ANOVA is quite robust for violations to homogeneity of variance. Nevertheless, the fact that the place task did not pass homogeneity test dictates caution in the interpretation of results.

7.2. Grooved Pegboard and Waterloo Handedness Questionnaire Correlations

Correlations were performed between the composite scores on the Waterloo-Handedness Questionnaire and performance on both the place and remove tasks of the Grooved Pegboard Test separately for younger and older adults.

7.3. Primary analysis of temporal variables and Euler angles

PV, TPV, TAPV and CD for wrist and mean range of motion for each joint were subjected to 3-way mixed measures analysis of variance (ANOVA) with between-subject factor “Group” (older versus younger) and “Hand” (right versus left) and “Task Condition” (pantomime versus tool) as within subject factors. Main effects of hand (Section 3.2.1), age (Section 3.2.2) and task condition (Section 3.2.3) were tested. Interaction effects between group and hand (Section 3.2.4), task condition and hand (Section 3.2.5), and group and condition were also quantified. The analysis also looked at 3 way interactions between group, hand, and task condition. Statistical analysis was done separately for each tool. The level of significance was set to $p<0.05$. Significant effects involving more than two independent measures were further analyzed using the Tukey HSD test ($p<0.05$).

7.4. Grooved Pegboard, Waterloo Handedness Questionnaire and Kinematics Correlations

Laterality quotients from the pegboard data, composite scores from the WHQ and laterality quotients derived for the PV, TPV, TAPV, CD and Euler angles for both cup and knife were correlated to reveal whether kinematic measures are sensitive and correlate well with the gold standard for handedness assessment (ie. Waterloo-Handedness Questionnaire and Grooved Pegboard). This was done separately for the pantomime and tool conditions, as well as younger and older adults. A stringent alpha level ($p < 0.001$) was selected due to the number of comparisons computed.

7.5. Angle-Angle, Velocity-Angle and Velocity-Velocity Analyses: Descriptive Statistics

Using mean Z-scores, shape values and RMSE scores, a mixed measures analysis of variance was used to determine main effects of hand, age and condition as well as any two-way and three-way interactions between main effects. The level of significance was set to $p < 0.01$ due to the number of comparisons computed.

7.6. Outliers

There were a couple of outliers in the present study. For the pegboard analysis, two older adults were excluded because their performance on both, place and remove task was slower relative to the rest of the group. In the cup ADL, all 50 individual data were included in the analysis. In the knife ADL, the analysis included only 20 younger adults and 12 older adults. One younger participant had trouble pantomiming the knife ADL. Eight younger adults were either performing the slicing gesture in the Y direction (up/down) or switched the primary axis of movement between pantomime and tool conditions (ie. pantomime was performed in X direction, tool condition was switched to Y direction). In terms of older adults, four older adults switched the primary axis of movement as mentioned previously for the younger adult group. Further, five older adults highly varied their axis of movement between the two conditions. Also, their movements were characterized by an increased number of sub-movements within each of the cycles in knife ADL. Hence, these older adults were not included in the statistical analysis.

8.0 Results

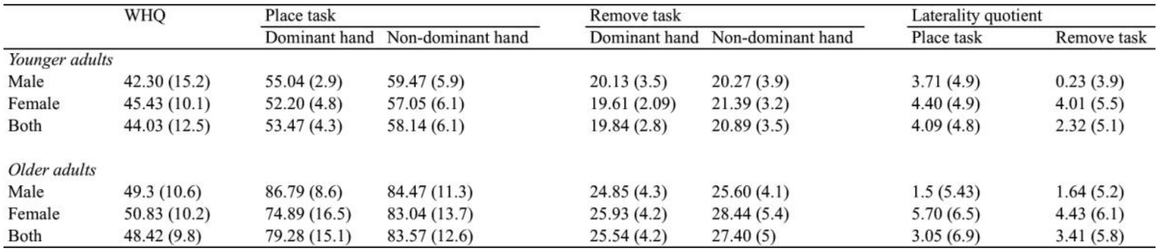
8.1. Waterloo Handedness Questionnaire (WHQ)

A group (young, old) by sex (male, female) mixed measures ANOVA was performed for WHQ scores. No significant differences were found between groups (p = 0.12), sex (p = 0.33) or group by sex interaction (p = 0.96) for laterality quotients for WHQ.

8.2. Grooved Pegboard

Overall results for the Grooved Pegboard and Waterloo-Handedness Questionnaire are presented in Table 3.

Table 3: Summary of Pegboard (place and remove tasks) and Waterloo Handedness data with standard deviations for younger and older adults.



	WHQ	Place task		Remove task		Laterality quotient	
		Dominant hand	Non-dominant hand	Dominant hand	Non-dominant hand	Place task	Remove task
Younger adults							
Male	42.30 (15.2)	55.04 (2.9)	59.47 (5.9)	20.13 (3.5)	20.27 (3.9)	3.71 (4.9)	0.23 (3.9)
Female	45.43 (10.1)	52.20 (4.8)	57.05 (6.1)	19.61 (2.09)	21.39 (3.2)	4.40 (4.9)	4.01 (5.5)
Both	44.03 (12.5)	53.47 (4.3)	58.14 (6.1)	19.84 (2.8)	20.89 (3.5)	4.09 (4.8)	2.32 (5.1)
Older adults							
Male	49.3 (10.6)	86.79 (8.6)	84.47 (11.3)	24.85 (4.3)	25.60 (4.1)	1.5 (5.43)	1.64 (5.2)
Female	50.83 (10.2)	74.89 (16.5)	83.04 (13.7)	25.93 (4.2)	28.44 (5.4)	5.70 (6.5)	4.43 (6.1)
Both	48.42 (9.8)	79.28 (15.1)	83.57 (12.6)	25.54 (4.2)	27.40 (5)	3.05 (6.9)	3.41 (5.8)

8.2.1. Place task

Significant main effects of hand, F (1,46) = 10.38, p = .0024, and age, F (1,46) = 104.29, p < .0001, existed. Further, sex by hand interactions [F(1,46) = 5.41, p = .0246] and age by sex by hand interactions [F(1,46) = 4.59, p = .0376] existed. Overall, older adults took longer time to complete the place task relative to younger adults. Further, females were faster than males for both hands and groups in completing the task.

However, for older adults, females were significantly faster than males in completing the place task with their dominant limb relative to non-dominant limb. Also, females in the older adult group were significantly faster at completing the task with their dominant limb relative to the non-dominant limb (refer to table 3).

8.2.2. Remove task

Significant main effects of hand, F (1,46) = 10.25, p < .0025, and age, F (1,46) = 29.49, p < .0001 existed. Further, sex by hand interaction existed [F(1,46) = 4.40, p = .0416]. Overall, older adults took longer time to complete the remove task. Females were slower at completing the remove task for the non-dominant limb relative to males, but took the same amount of time to complete the task with their dominant limb relative to males (refer to table 3).

8.3. Correlations between Grooved Pegboard and Waterloo Handedness Questionnaire

No significant correlations existed for place (YA: p = .197; OA: p = .08) and remove (YA: p = .92; OA: p = .11) tasks in younger and older adults.

8.4. Overall Summary for Grooved Pegboard and WHQ

Overall, older adults’ performance on both, place and remove tasks was slower relative to younger adults. Further, the dominant limb performed both tasks faster than non-dominant limb in both groups. In the place task, females were faster at completing the task relative to males in both groups. However, for the remove task, females were slower at completing the task with the non-dominant limb relative to males.

8.5. Kinematic Analysis: Cup ADL

This section of results will focus on the main effects of hand, age, condition and interaction effects between age, hand and condition. For a summary of significant results for the cup ADL, please refer to Table 4. A full summary of results is in Appendix E.

Table 4: Statistical analyses for temporal and spatial kinematics in use phase of cup ADL.

Measure	Main effect hand	Main effect condition	Main Effect Age	Age x Condition	Age x Hand	Hand x Condition
Temporal Measures						
Peak Velocity						
- up (+Y)	F(1,48) = 10.6, *p* < .01	F(1,48) = 27.3, *p* < .01	F(1,48) = 24.2, *p* < .01			
- down (-Y)			F(1,48) = 22.3, *p* <.01			
Cycle Up						
Time to PV			F(1,48) = 19.2, *p* <.01			F(1,48) = 4.4, *p* =.03
Time after PV		F(1,48) = 48.2, *p* <.01	F(1,48) = 5.8, *p* = .01			
Cycle Duration		F(1,48) = 32.1, *p* < .01	F(1,48) = 15.3, *p* < .01			
% Movement time						
Cycle Down						
Time to PV	F(1,48) = 6.5, *p* = .01		F(1,48) = 14.1, *p* < .01			
Time after PV	F(1,48) = 10.9, *p* < .01	F(1,48) = 5.6, p = .02	F(1,48) = 6.9, *p* = .01		F(1,48) = 6.7, p = .01	
Cycle Duration			F(1,48) = 15.2, *p* < .01			
% Movement time						
Joint Angles						
Shoulder Elevation	F(1,48) = 12.8, *p* < .01			F(1,48) = 5.9, *p* =.01		
Shoulder Plane	F(1,48) = 18.6, *p* < .01		F(1,48) = 10.4, *p* < .01			F(1,48) = 8.8, *p* < .01
Shoulder Axial Rot.			F(1,48) = 18.3, *p* = .001		F(1, 48) = 6.4, *p* = .01	
Elbow Flexion						
Forearm Pron/Sup.	F (1,48) = 4.3, *p* < .01	F(1,48) = 10.1, *p* < .01			F(1,48) = 5.8, *p* = .01	
Wrist Flexion	F(1,48) = 5.9, *p* = .01	F(1,48) = 14.9, *p* < .01				
Wrist Rad/Ulnar Dev.	F(1,48) = 11.1, *p* < .01				F(1,48) = 3.8, *p* = .05	
Wrist Pronation						

8.6. Temporal Aspects of Movement in Use Phase

8.6.1. Peak Velocity Toward/Away from the Mouth (+Y direction (Up) and –Y direction (down) respectively; Please refer to Figure 4 in Methods Section)

Main effects of age, hand and condition existed for PV while moving the cup towards the mouth (Table 4). Older adults had lower PV relative to younger adults (OA: 385 ± 145 mm/s; YA: 588 ± 163 mm/s). Further, the non-dominant arm had higher peak velocities relative to the dominant arm (ND: 499 ± 188 mm/s; DM: 474 ± 183 mm/s). The pantomime condition produced higher peak velocities (panto: 519 ± 197 mm/s; tool: 454 ± 167 mm/s).

Further, main effects of age existed for PV achieved during the movement of the cup away from mouth towards the table. Overall, older adults had lower peak velocities relative to younger adults (OA: 455 ± 138 mm/s; YA: 675 ± 196 mm/s).

8.6.2. Temporal Aspects of Movement for First Cycle (Towards the Mouth/ +Y direction)

A main effect of age existed for TPV, TAPV and CD for the first cycle of movement (Table 4). Older adults took longer time to reach peak velocity (OA: 785.6 ± 385 ms; YA: 499 ± 153 ms); had longer time after peak velocity (OA: 1040 ± 415 ms; YA: 808 ± 339 ms); and thus, had longer cycle duration (OA: 1826 ± 638 ms; YA: 1307 ± 393 ms). Further, a main effect of condition existed for TAPV and CD. Tool condition had longer time after peak velocity relative to the pantomime condition (panto: 811 ± 349 ms; tool: 1037 ± 395 ms), as well as longer cycle duration (panto: 1445 ± 540 ms; tool: 1688 ± 576 ms).

An interaction effect existed between condition and hand for TPV (Figure 7), such that the non-dominant hand took longer time to reach peak velocity in the pantomime condition (642 ± 345 ms) relative to the dominant hand in the same condition (580 ± 264 ms). In the tool condition, the effect was reversed, as the dominant hand took longer time to reach peak velocity relative to the non-dominant hand (ND: 620 ± 314 ms; DM: 636 ± 315 ms).

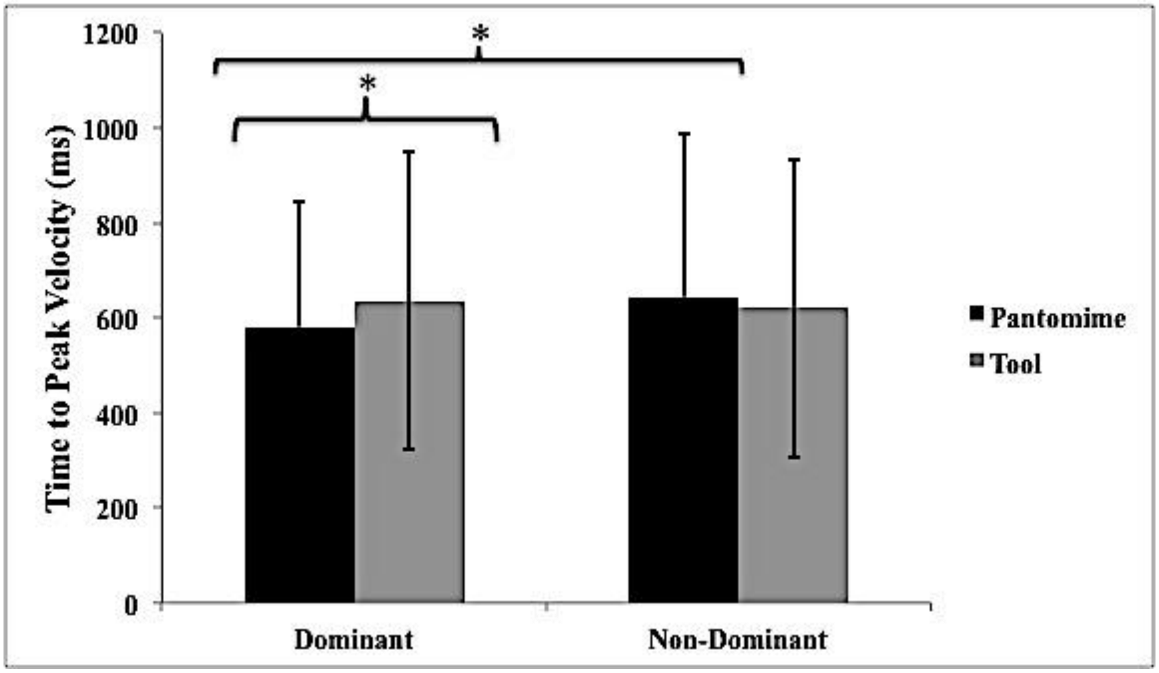


Figure 7: Interaction effect of hand and condition for time to peak velocity with standard deviation in the first cycle of movement in the cup ADL with standard deviations. An asterisk over the two components indicates it was significantly different (*: $p < 0.05$; **: $p < 0.01$; ***: $p < 0.001$). Significant differences were tested at $p \leq 0.05$.

8.6.3. Temporal Aspects of Movement for Second Cycle (Away from Mouth/ -Y Direction)

Main effect of age existed for TPV, TAPV and CD for the second cycle of movement (Table 4). Overall, older adults took longer time to reach peak velocity (OA: 906 ± 391 ms; YA: 604 ± 246 ms); had longer time after peak velocity (OA: 731 ± 272 ms; YA: 592 ± 189 ms); and thus, had longer cycle duration (OA: 1637 ± 573 ms; YA: 1195 ± 326 ms).

A main effect of hand also existed for TPV and TAPV. Dominant hand took longer time to reach peak velocity relative to the non-dominant hand (ND: 713 ± 347 ms; DM: 748 ± 351 ms). On the other hand, non-dominant hand had longer time after peak velocity relative to the dominant hand (ND: 671 ± 248 ms; DM: 629 ± 225 ms). A main effect of condition also existed for TAPV. TAPV was longer in the tool condition (panto: 625 ± 278 ms; tool: 698 ± 180 ms).

An interaction effect existed between the age and hand for TAPV (Figure 8). The non-dominant hand of older adults took longer time after peak velocity relative to the dominant hand (ND: 774 ± 285 ms; DM: 688 ± 253 ms). There were no differences between the hands in younger adults (ND: 597 ± 186 ms; DM: 586 ± 193 ms). Overall, older adults took longer time after peak velocity.

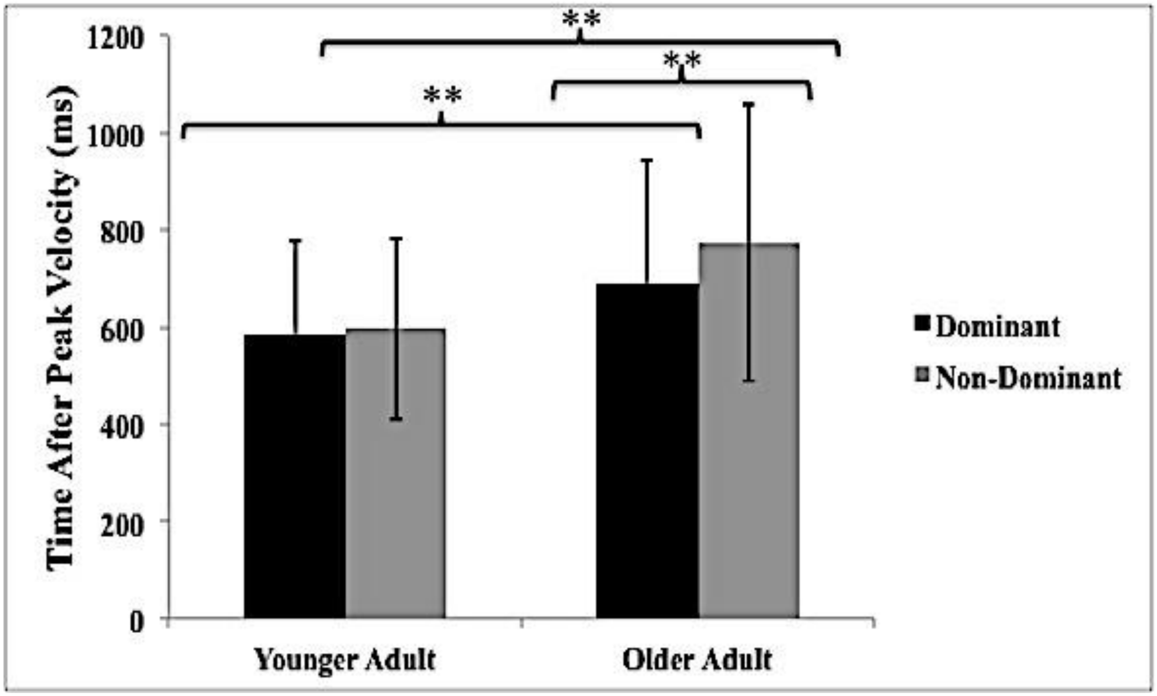


Figure 8: Interaction effect of hand and age for time after peak velocity in the second cycle of movement in the cup ADL with standard deviations. An asterisk over the two components indicates it was significantly different (*: $p < 0.05$; **: $p < 0.01$; ***: $p < 0.001$). Significant differences were tested at $p \leq 0.05$.

8.6.4. Pegboard, Waterloo Handedness Questionnaire and Temporal Aspects of Movement Correlations

Regression analyses were run between Grooved Pegboard laterality quotients and temporal measure laterality quotients, as well as WHQ and temporal movement laterality quotients. No significant correlations existed.

8.6.5. Overall Summary for Temporal Aspects of Movement in Cup ADL

Overall, older adults had lower PV, longer TPV, TAPV and CD relative to younger adults in both cycles of movement. Pantomime condition produced higher PVs in both cycles of movement. Tool condition had longer TAPV and CD relative to pantomime condition in both cycles. A main effect of hand existed for second cycle of movement (e.g. putting cup down), where non-dominant limb exhibited longer TAPV and dominant limb had longer TPV. Also, a main effect was found for PV while moving cup towards the mouth, where the non-dominant arm had higher peak velocity relative to the dominant arm.

No dependent measures correlated with either one of the tasks on the Grooved Pegboard (place and remove), nor scores on the WHQ.

8.7. Angular Aspects of Movement in Use Phase

8.7.1. Range of Motion at the Shoulder

A main effect of hand existed for shoulder elevation and shoulder plane of elevation (Table 4). In terms of shoulder elevation, the dominant arm had higher range of shoulder elevation (DM: 13 ± 5°; ND: 11 ± 5°). Further, range of plane of elevation (i.e. reaching out towards a shelve) was larger in the dominant arm (DM: 29 ± 11°; ND: 25 ± 11°). A main effect of age existed for range of plane of elevation and axial rotation (Table 4). Older adults had a reduced range of plane of elevation relative to younger adults (OA: 23 ± 10°; YA: 31 ± 11°). Further, older adults had higher range of axial rotation relative to younger adults (OA: 19 ± 8 ms; YA: 13 ± 5 ms).

Age by hand interaction effect was quantified for internal/external rotation of the arm (Figure 9). Older adults had two times higher mean range of internal/external rotation (21 ± 9°) in the non-dominant arm, relative to younger adults with their non-dominant arm (12 ± 4°). When using their dominant arm, older adults had more internal/external rotation (17.6 ± 7°) than younger adults (13.8 ± 5.5°). Post-hoc analyses showed that the significant differences between the hands were only present in older adults.

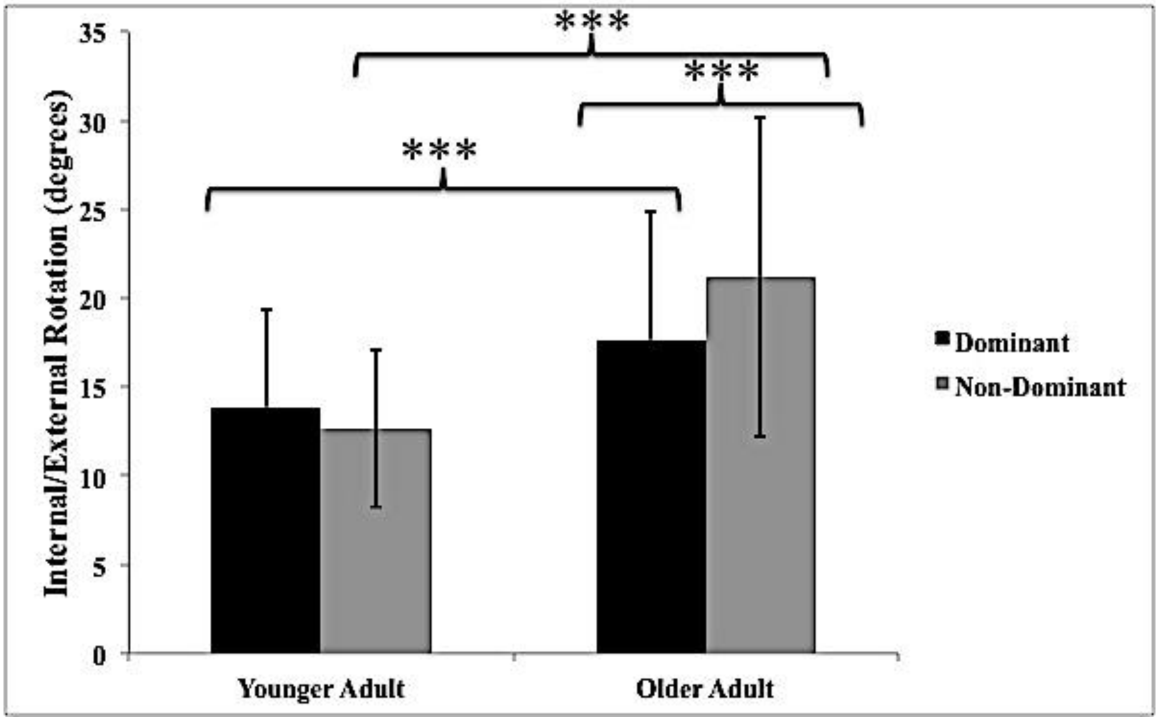


Figure 9: Interaction effect of hand and age for internal/external rotation of the forearm in the cup ADL with standard deviations. An asterisk over the two components indicates it was significantly different (*: $p < 0.05$; **: $p < 0.01$; ***: $p < 0.001$). Significant differences were tested at $p \leq 0.05$.

Further, age by condition interaction existed for shoulder elevation (Figure 10). In the pantomime condition, younger and older adults had approximately the same range of shoulder elevation (YA:11 ± 5°; OA: 12 ± 5°). However, once the cup was introduced, older adults produced a higher range of shoulder elevation (OA: 14 ± 5°; YA: 11 ± 5°). Post-hoc analyses revealed that the task condition only affected the ROM in older adults.

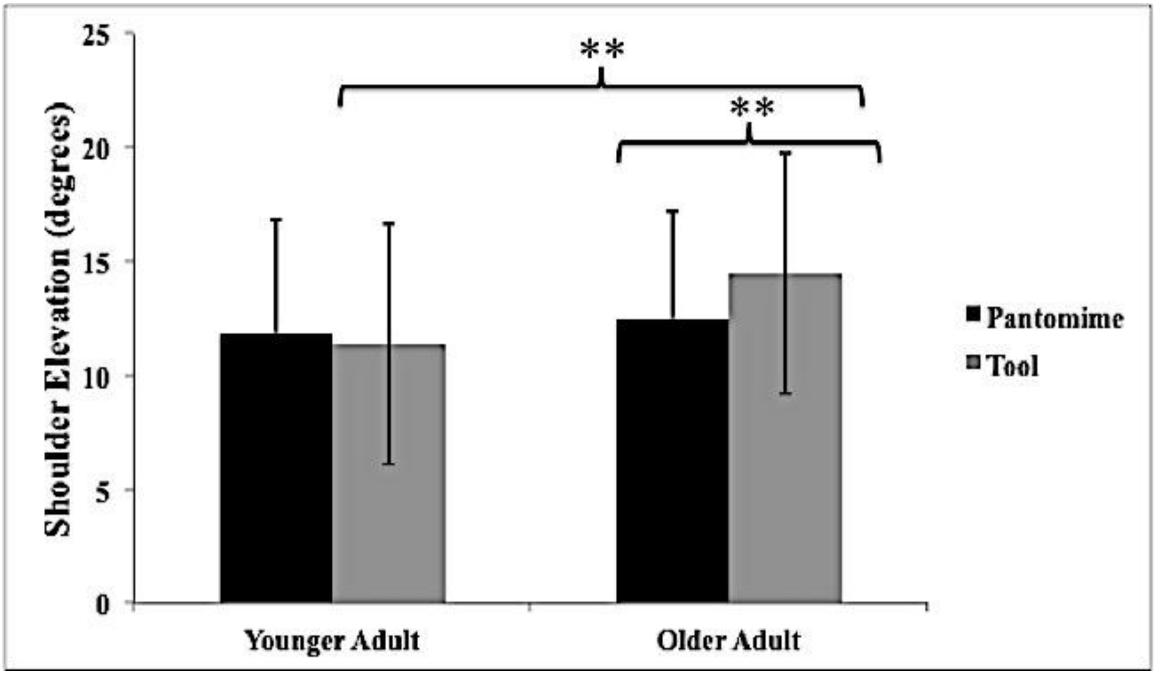


Figure 10: Interaction effect of condition and age for shoulder elevation in the cup ADL with standard deviations. An asterisk over the two components indicates it was significantly different (*: $p < 0.05$; **: $p < 0.01$; ***: $p < 0.001$). Significant differences were tested at $p \leq 0.05$.

Hand by condition interaction effect existed for shoulder plane of elevation (Figure 11). Dominant limb produced higher mean range of shoulder plane of elevation in the pantomime condition relative to the non-dominant limb in the same condition (ND: 25 ± 12°; DM: 31 ± 12°). Differences between the two limbs were larger in the pantomime condition relative to the tool condition (ND: 26 ± 9°; DM: 31 ± 12°). Post-hoc analyses revealed that the significant differences between the limbs were only present in the pantomime condition.

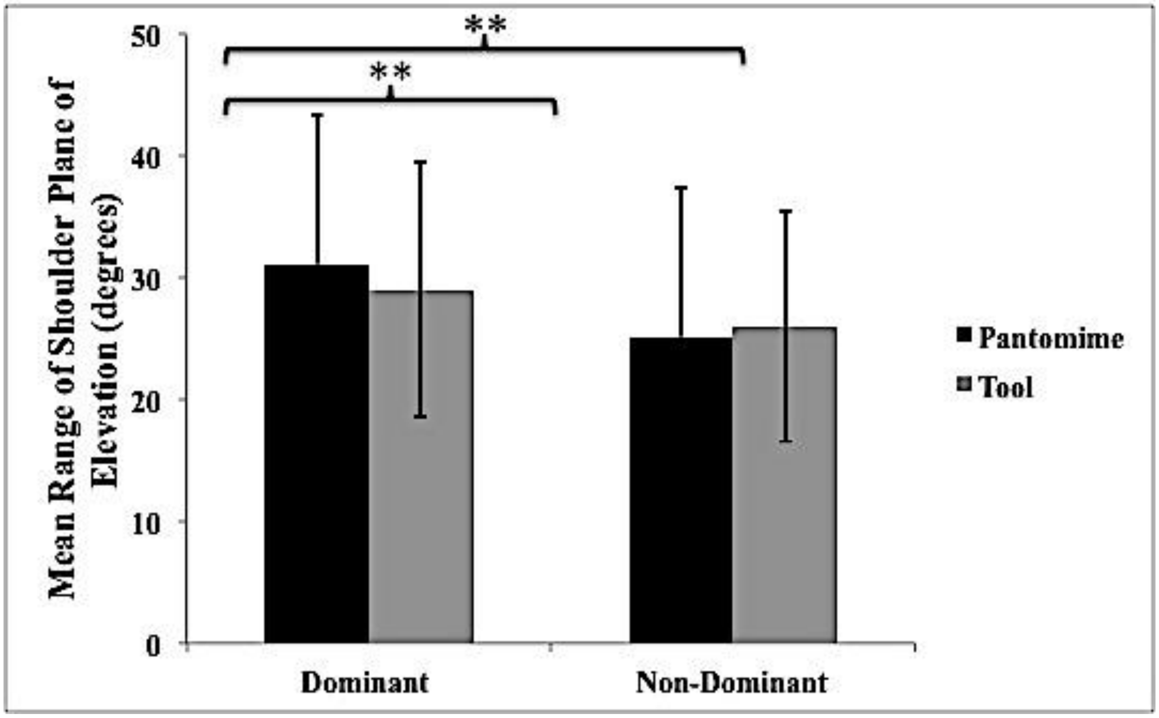


Figure 11: Interaction effect of hand and condition for mean range of shoulder plane of elevation in the cup ADL with standard deviations. An asterisk over the two components indicates it was significantly different (*: $p < 0.05$; **: $p < 0.01$; ***: $p < 0.001$). Significant differences were tested at $p \leq 0.05$.

8.7.2. Range of Motion at the Elbow

Main effect of condition and hand existed for range of forearm pronation/supination (Table 4). Non-dominant hand had a higher mean range of forearm pronation/supination relative to the dominant hand (ND: 34 ± 15°; DM: 32 ± 13°). Pantomime condition produced higher range of pronation/supination relative to tool (panto: 36 ± 16°; tool: 31 ± 11°).

Further, age by hand interaction existed for forearm supination/pronation (Figure 12). There were no differences between the dominant and non-dominant limbs in younger adults (DM: 30 ± 12°; ND: 30 ± 12.6°). However, differences between the two hands were quantified in older adults (DM: 39 ± 14°; ND: 34 ± 16°). Interestingly, no significant effects were quantified for elbow flexion/extension.

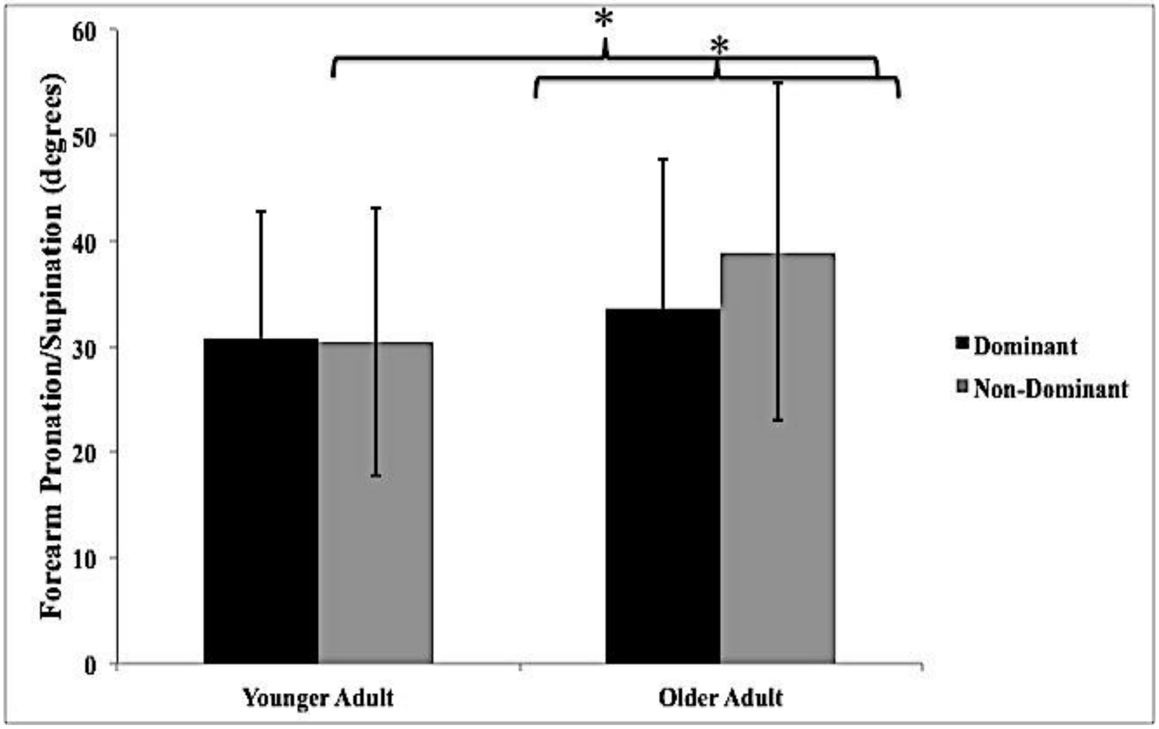


Figure 12: Interaction effect of hand and age for forearm pronation/supination in the cup ADL with standard deviations. An asterisk over the two components indicates it was significantly different (*: $p < 0.05$; **: $p < 0.01$; ***: $p < 0.001$). Significant differences were tested at $p \leq 0.05$.

Age by hand interaction effect was quantified for mean range of forearm pronation/supination. Older adults had higher mean range of forearm pronation/supination while using a cup with a non-dominant limb (39 ± 16°) relative to the dominant limb (34 ± 14°). On the other hand, younger adults had similar mean range of pronation/supination between the two limbs (ND: 30 ± 13°; DM: 31 ± 12°). Post-hoc analyses showed that the significant differences between the hands were only present in older adults.

8.7.3. Range of Motion at the Wrist

A main effect of hand existed for radial/ulnar deviation of the wrist and flexion/extension of the wrist (Table 4). Overall, the dominant arm produced a higher range of motion in all three rotations at the wrist (Table 5). Further, a main effect of condition was quantified for range of wrist flexion/extension. In the pantomime condition, participants had a higher range of wrist flexion/extension relative to tool condition (panto: 19 ± 10°; tool: 15 ± 7°).

Table 5: Range of motion at the wrist for dominant and non-dominant hands in the cup ADL.

Measure	**Dominant Hand (°)**	**Non-Dominant Hand (°)**
Radial/Ulnar Deviation	23 ± 12	19 ± 10
Flexion/Extension	18 ± 10	15 ± 8

A three-way interaction existed between the hand, condition and age for mean range of wrist flexion/extension. The non-dominant arm had lower mean range of wrist flexion/extension in younger adult group in tool and pantomime conditions (panto, YA, ND: 16°; panto, YA, DM: 20°; tool, YA, ND: 14°; tool, YA, DM: 17°). There were no differences between limbs in older adults for the pantomime condition (panto, OA, ND: 19°; panto, OA, DM: 19°). However, differences between limbs emerged in the tool condition in the older adult group, where the non-dominant limb had lower mean range of wrist flexion/extension (tool, OA, ND: 13°; tool, OA, DM: 16°).

8.7.4. Pegboard, Waterloo Handedness Questionnaire and Angular Aspects of Movement Correlations

Regression analyses revealed a significant correlation between place task on the grooved pegboard and mean range of internal/external rotation at the shoulder for pantomime condition (r = 0.67, *p* = .0008) (Figure 13).

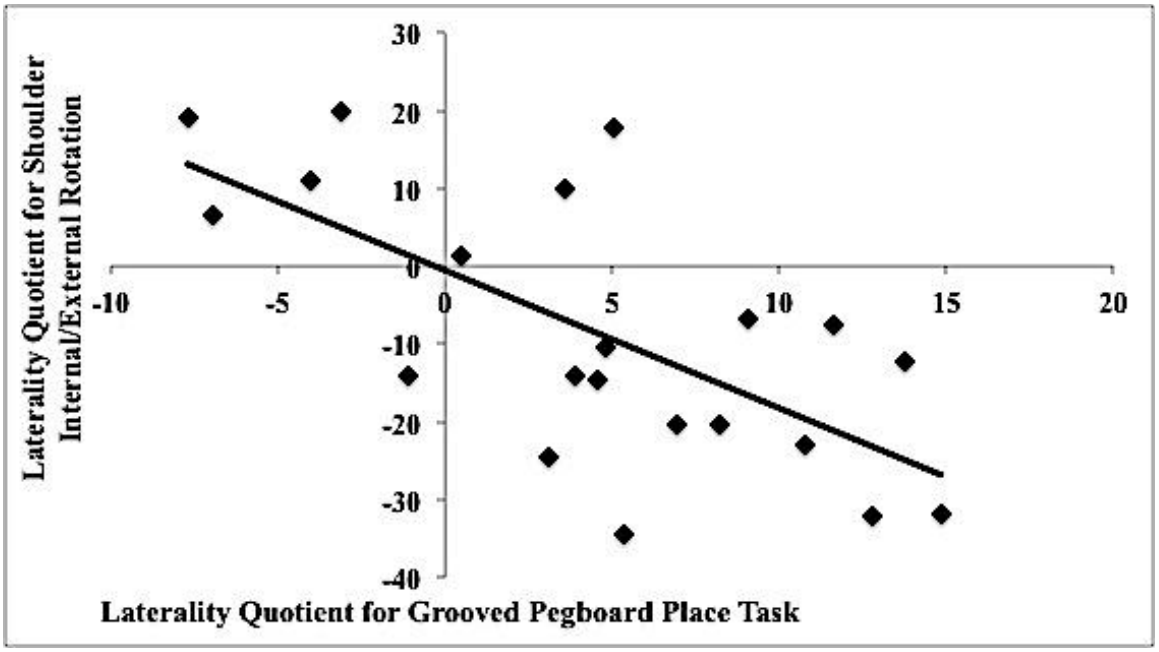


Figure 13: Correlation between place task laterality quotient in the grooved pegboard and mean range of internal/external rotation in degrees in the pantomime condition for older adults.

8.7.5. Overall Summary for Angular Aspects of Movement in Cup ADL

In summary, differences between dominant and non-dominant limbs were only quantified in older adults for ROM of external/internal rotation and forearm pronation/supination. Older adults had reduced ROM in terms of shoulder elevation relative to younger adults. However, they produced increased ROM for internal/external rotation at the shoulder in comparison to younger adults. In terms of condition effects, pantomime condition produced higher ROM for forearm pronation/supination and wrist flexion/extension. Interaction effect was present between condition and hand for shoulder elevation. Tool condition reduced the mean ROM in the dominant limb, but not in the non-dominant limb.

Correlations revealed that place task for the Grooved Pegboard had a strong relationship only with mean range of internal/external rotation at the shoulder.

8.8. Interjoint Coordination: Cup ADL

In the methodology, it was proposed to examine interjoint coordination during cup manipulation in both groups of individuals in different task conditions. However, the non-cyclical nature of the movement precluded this sort of analyses and thus, the data was not conducive to interjoint coordination analyses. To date, interjoint coordination in the cup ADL has only been examined in the reach phase of movement (Alt Murphy et al., 2010). Hence, better methods should be developed to examine interjoint coordination during the actual manipulation of the cup.

9.0. Kinematic Analysis: Knife ADL

This section of results will focus on the main effects of hand, age, condition and interaction effects between age, hand and condition. For a summary of significant results for the knife ADL, please refer to Table 6. Full summary of results can be found in Appendix F.

Table 6: Statistical analyses for temporal and spatial kinematics in use phase of knife ADL. These analyses included 12 older adults and 20 younger adults, and were performed only on participants whose primary axis of movement was in X direction (forward/backward).

Measure	Main effect hand	Main effect condition	Main Effect Age	Age*Condition	Age*Hand	Hand*Condition
Temporal Measures						
Peak Velocity						
- away (+X)						
- towards (-X)						F(1,30) = 7.6, $p < .01$
Cycle						
Time to PV	F(1,30) = 6.9, $p = .01$					
Time after PV			F(1,30) = 10, $p = .003$			
Cycle Duration	F(1,30) = 6.3, $p = .01$		F(1,30) = 8.9, $p = .005$			
Joint Angles						
Shoulder Elevation	F(1,30) = 37.1, $p < .0001$	F(1,30) = 14.8, $p = .0006$			F(1,30) = 6.6, $p = .01$	F(1,30) = 10.5, $p < .01$
Shoulder Plane	F(1,30) = 30.7, $p < .0001$					
Shoulder Axial Rot.			F(1,30) = 4.6, $p = .03$	F(1,30) = 6.6, $p = .01$		
Elbow Flexion						F(1,30) = 5.7, $p = .02$
Forearm Pron/Sup.		F(1,30) = 14.6, $p = .0006$				
Wrist Flexion		F(1,30) = 17.8, $p = .0002$		F(1,30) = 15.1, $p = .0005$		
Wrist Rad/Ulnar Dev.		F(1,30) = 18.6, $p = .0002$		F(1,30) = 5, $p = .03$		
Wrist Pronation		F(1,30) = 12.6, $p = .0001$		F(1,30) = 7.3, $p = .01$	F(1,30) = 4.2, $p = .04$	

9.1. Temporal Aspects of Movement in Use Phase

9.1.1. Peak Velocities Away and Towards the Body (+X direction and –X direction respectively)

An interaction effect between hand and condition existed for peak velocity at the wrist during towards the body movement in the knife ADL (Table 6; Figure 14). Both, the dominant and non-dominant limbs had higher peak velocity in the pantomime condition (ND: 606 ± 250 mm/s; DM: 570 ± 245 mm/s). Once the tool was introduced, peak velocity decreased in both limbs (ND: 563 ± 232 mm/s; DM: 549 ± 219 mm/s). This decrease in peak velocity was larger in the non-dominant limb.

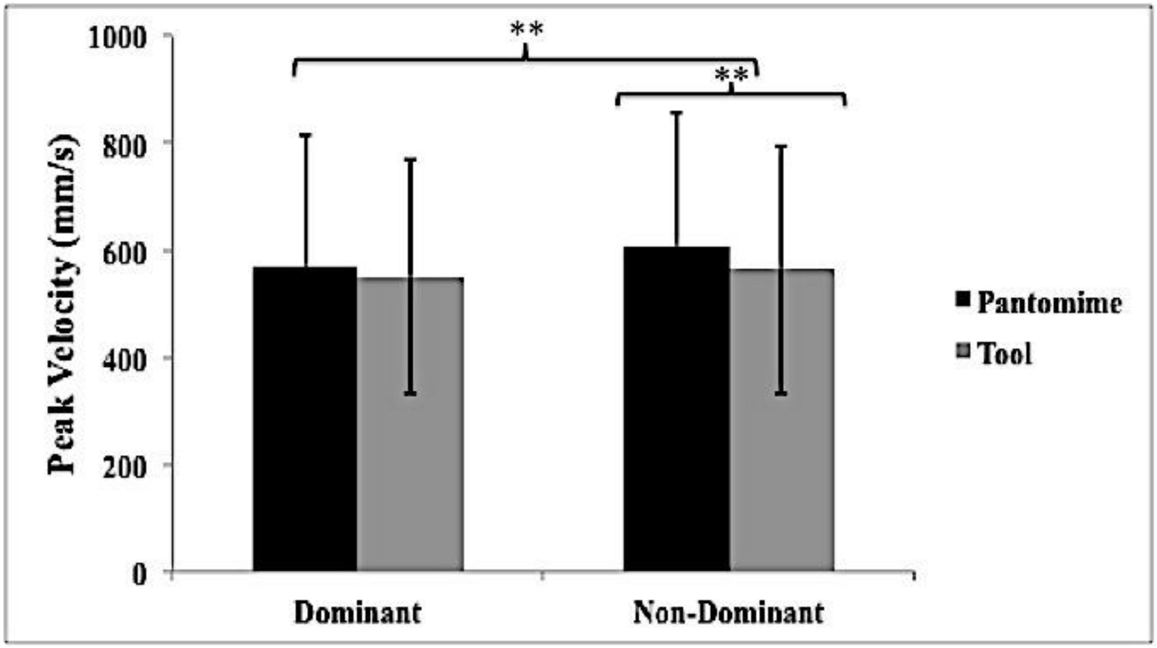


Figure 14: Interaction effect of hand and condition for peak velocity towards the body in the knife ADL with standard deviations. An asterisk over the two components indicates it was significantly different (*: $p < 0.05$; **: $p < 0.01$; ***: $p < 0.001$). Significant differences were tested at $p \leq 0.05$.

9.1.2. Temporal Aspects of Movement within a Cycle

Main effect of age existed for TAPV and CD (Table 6). Older adults had longer TAPV (OA: 568 ± 184 ms; YA: 410 ± 104 ms) and their CD was prolonged due to this (OA: 1050 ± 295 ms; YA: 799 ± 186 ms).

Further main effect of hand existed for TPV and CD (Table 6). Non-dominant limb took longer time to reach peak velocity relative to the dominant limb (ND: 429 ± 114 ms; DM: 420 ± 108 ms). Therefore, the non-dominant limb had longer CD relative to the dominant limb (ND: 902 ± 268 ms; DM: 884 ± 256 ms).

9.1.3. Grooved Pegboard, Waterloo Handedness Questionnaire and Temporal Aspects of Movement Correlations

Regression analyses were run between Grooved Pegboard laterality quotients and temporal measure laterality quotients, as well as WHQ and temporal movement laterality quotients. No significant correlations existed.

9.1.4. Overall Summary for Temporal Aspects of Movement in Knife ADL

To summarize, the dominant and non-dominant limbs had higher peak velocities in the pantomime condition relative to the tool condition. The decrement in peak velocity was larger for the non-dominant limb when the tool was introduced. Also, the non-dominant limb took longer time to reach peak velocity and thus, had longer cycle duration relative to the dominant limb. Further, older adults had longer TAPV and CD.

9.2. Angular Aspects of Movement in Use Phase

9.2.1. Range of Motion at the Shoulder

Main effects for hand existed for shoulder elevation and shoulder plane of elevation (Table 6). The non-dominant arm had larger range of shoulder elevation (ND: 13 ± 7°; DM: 9 ± 6°). Further, non-dominant limb also had higher range of shoulder flexion (28 ± 10°) in comparison to the dominant limb (22 ± 10°). Main effect of condition was only present for range of shoulder elevation (Table 6), where pantomime condition had higher range of shoulder elevation (panto: 12 ± 7°; tool: 10 ± 7°). Main effect of age existed for range of internal/external rotation, where younger adults had higher range of internal/external rotation (YA: 14 ± 7°; OA: 9 ± 6°).

In terms of interactions, age by hand interaction existed for shoulder elevation and age by condition interaction for internal/external rotation. Younger adults had higher range of shoulder elevation in their non-dominant arm (12 ± 6°) relative to their dominant arm (10 ± 6°). This was also the case with older adults, as their non-dominant arm produced higher range of shoulder elevation (ND: 14 ± 8.5°; DM: 9 ± 4.5°) (Figure 15). Overall, a greater hand effect existed in older adults.

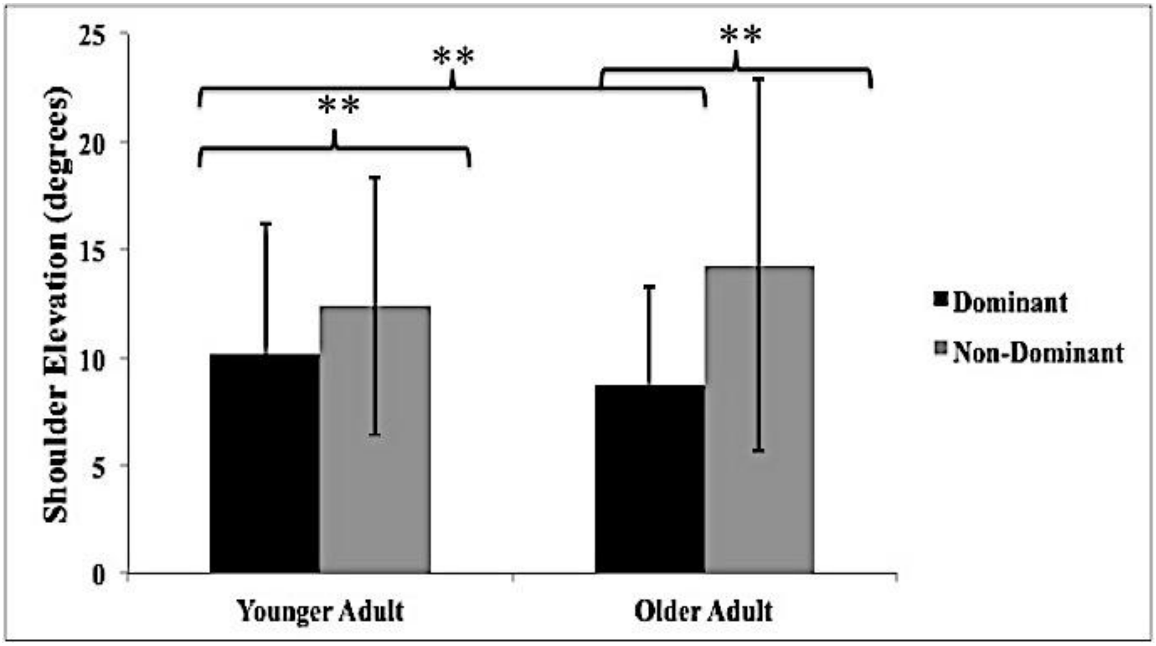


Figure 15: Interaction effect of hand and condition for range of shoulder elevation in knife ADL with standard deviations. An asterisk over the two components indicates it was significantly different (*: $p < 0.05$; **: $p < 0.01$; ***: $p < 0.001$). Significant differences were tested at $p \leq 0.05$.

For internal/external rotation, there were no differences for range of motion between pantomime and tool conditions in older adults (panto: 9° ± 4; tool: 9 ± 7°). However, higher range of internal/external rotation was quantified in younger adults in pantomime condition (panto: 15 ± 7°; tool: 13 ± 7°) (Figure 16).

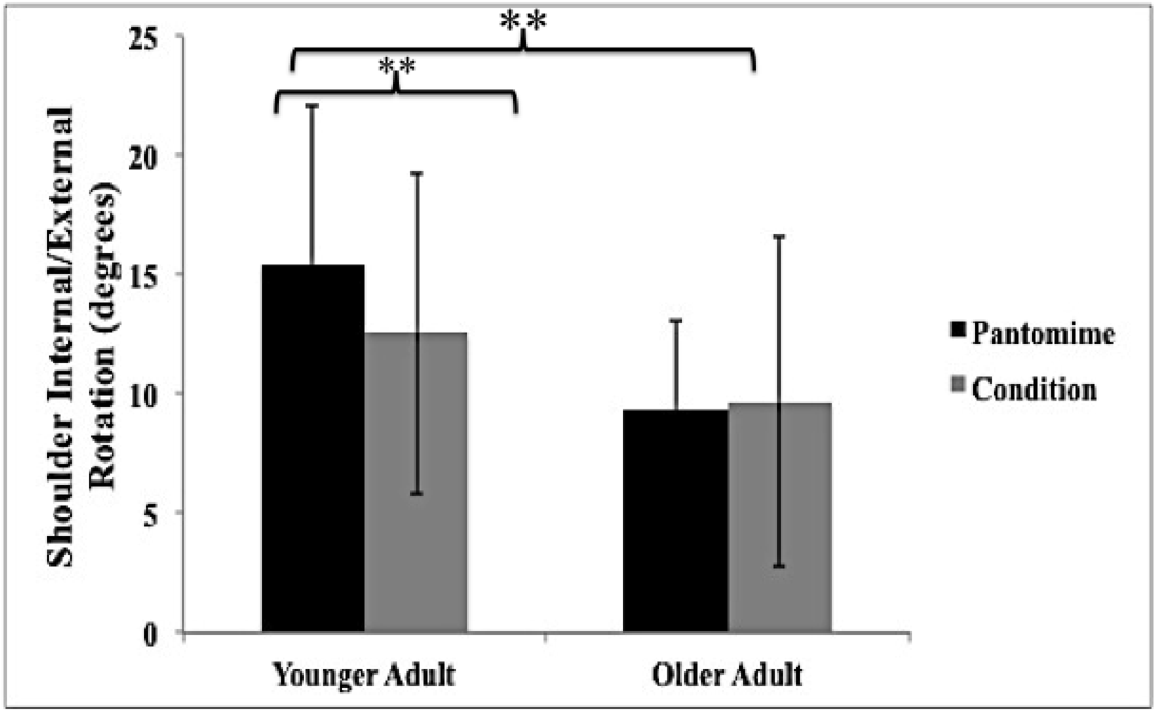


Figure 16: Interaction effect for age and condition for range of axial rotation in knife ADL with standard deviations. An asterisk over the two components indicates it was significantly different (*: $p < 0.05$; **: $p < 0.01$; ***: $p < 0.001$). Significant differences were tested at $p \leq 0.05$.

Hand by condition interaction existed for mean range of shoulder elevation (Figure 17). ROM was higher in the pantomime condition in the non-dominant limb relative to the tool condition (panto: 15 ± 8°; tool: 12 ± 6°). In the dominant limb, the difference between the two conditions did not exist (panto: 10 ± 6°; tool: 9 ± 5°).

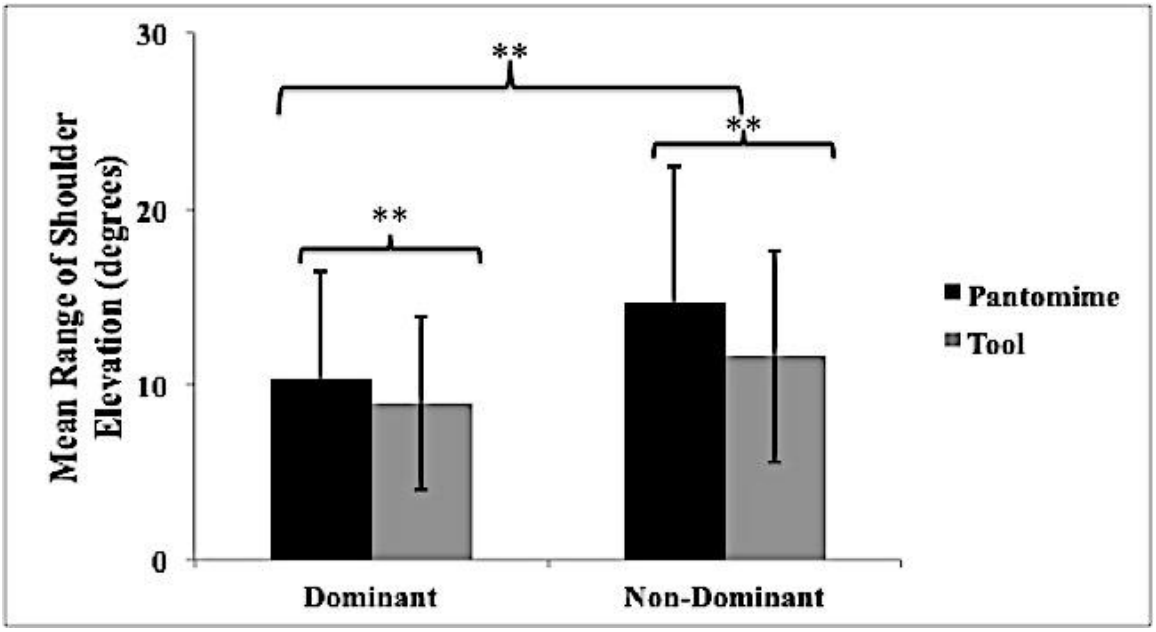


Figure 17: Interaction effect for hand and condition for mean range of shoulder elevation in knife ADL with standard deviations. An asterisk over the two components indicates it was significantly different (*: $p < 0.05$; **: $p < 0.01$; ***: $p < 0.001$). Significant differences were tested at $p \leq 0.05$.

9.2.2. Range of Motion at the Elbow

Main effect of condition existed for range of forearm pronation/supination (Table 6). Pantomime condition produced higher range of pronation/supination (11 ± 6°) relative to the tool condition (9 ± 5°).

Hand by condition interaction effect existed for mean range of elbow flexion/extension (Figure 18). No differences between the conditions were present in the non-dominant limb (panto: 35 ± 12°; tool: 34 ± 14°). In the dominant limb, tool condition contributed to higher mean range of elbow flexion/extension (panto: 33 ± 12°; tool: 34 ± 14°).

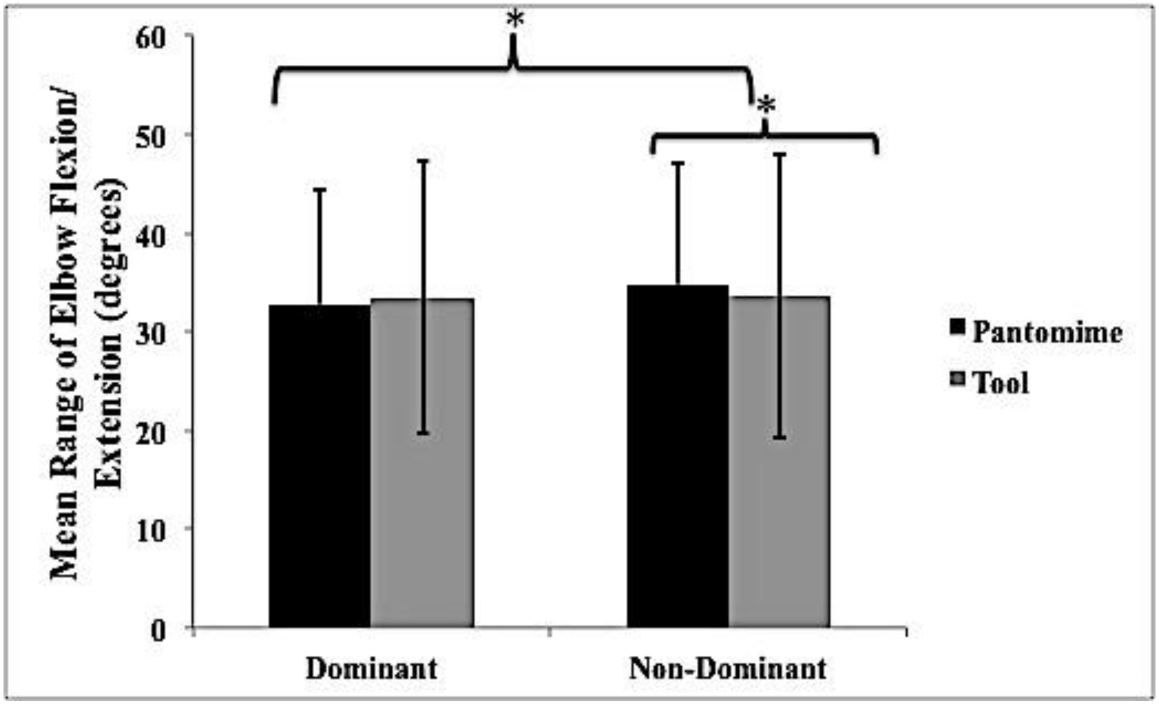


Figure 18: Interaction effect for hand and condition for mean range of elbow flexion/extension in knife ADL with standard deviations. An asterisk over the two components indicates it was significantly different (*: $p < 0.05$; **: $p < 0.01$; ***: $p < 0.001$). Significant differences were tested at $p \leq 0.05$.

9.2.3. Range of Motion at the Wrist

A main effect of condition existed for range of radial/ulnar deviation (Table 6). Overall, pantomime condition produced lower ROM for mean range of radial/ulnar deviation (panto: 10 ± 7°; tool: 17 ± 10°).

Further, for range of radial/ulnar deviation at the wrist, older adults had higher ROM in the tool condition (20 ± 16°) relative to the pantomime condition (11 ± 7°). The pattern was the same for younger adults (panto: 10 ± 6°; tool: 13 ± 6). In terms of range of pronation/supination, older adults had less range of motion in the pantomime (panto:

11 ± 5°; tool: 16 ± 9°). There were no differences between the task conditions for younger adults (panto: 12 ± 10°; tool: 13 ± 10°).

9.2.4. Grooved Pegboard, Waterloo Handedness Questionnaire and Angular Aspects of Movement Correlations

Regression analyses revealed no significant correlations between WHQ scores, place and remove tasks on the grooved pegboard and mean range of shoulder/elbow/wrist rotations.

9.2.5. Overall Summary for Angular Aspects of Movement in Knife ADL

Overall differences between dominant and non-dominant arms in terms of range of motion were found for shoulder elevation and shoulder plane of elevation. Non-dominant arm consistently had higher ROM relative to dominant arm. In terms of aging effect on manual asymmetries, differences between limbs were greater in older adults for mean range of shoulder elevation.

Tool condition produced higher ROM in older adults for wrist flexion/extension wrist radial/ulnar deviation, and elbow flexion/extension.

Correlation analyses revealed that there is no relationship between both tasks on Grooved Pegboard, WHQ and angular dependent measures.

9.3. Interjoint Coordination: Knife ADL

Overall picture of joint motions is presented in Figures 19-24. These plots represent kinematic relationships among joint angles and wrist and elbow velocities for pantomime and tool conditions of both dominant and non-dominant arms. Elbow flexion/extension is plotted against upper arm elevation in order to depict a relationship between elbow and shoulder motions (Figures 19 and 22). Further, elbow flexion/extension is plotted against wrist velocity in order to represent the relationship between angular motion at the elbow and wrist velocity (Figure 20 and 23). In this case, wrist velocity is determined by the combined effect of shoulder and elbow motions. Lastly, wrist velocity is plotted against elbow velocity to capture the degree of temporal coupling between the movements at these joints (Figure 21 and 24).

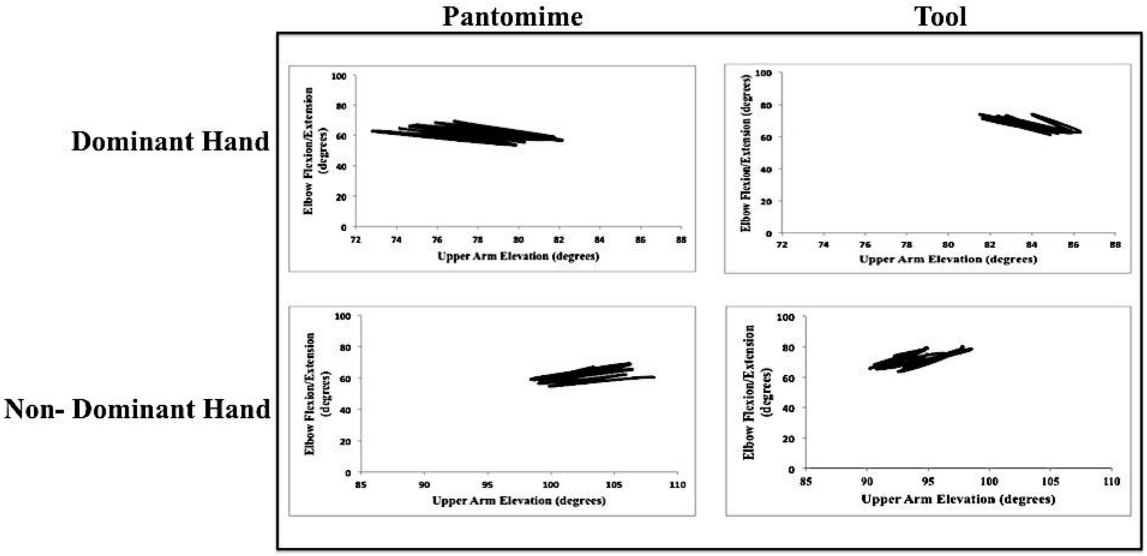


Figure 19: Kinematic relationship between joint angles (shoulder and elbow) in pantomime and tool conditions for dominant and non-dominant hands in younger adult. This example is for one trial only.

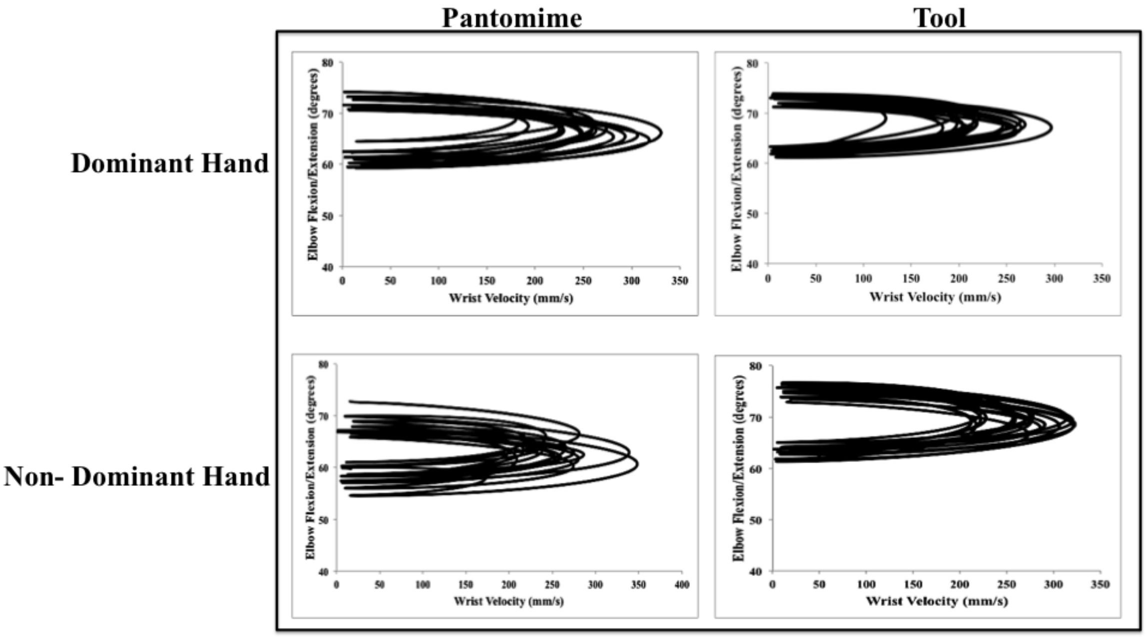


Figure 20: Kinematic relationship between elbow flexion/extension and wrist velocity in pantomime and tool conditions for dominant and non-dominant hands in younger adult. This example is for one trial only.

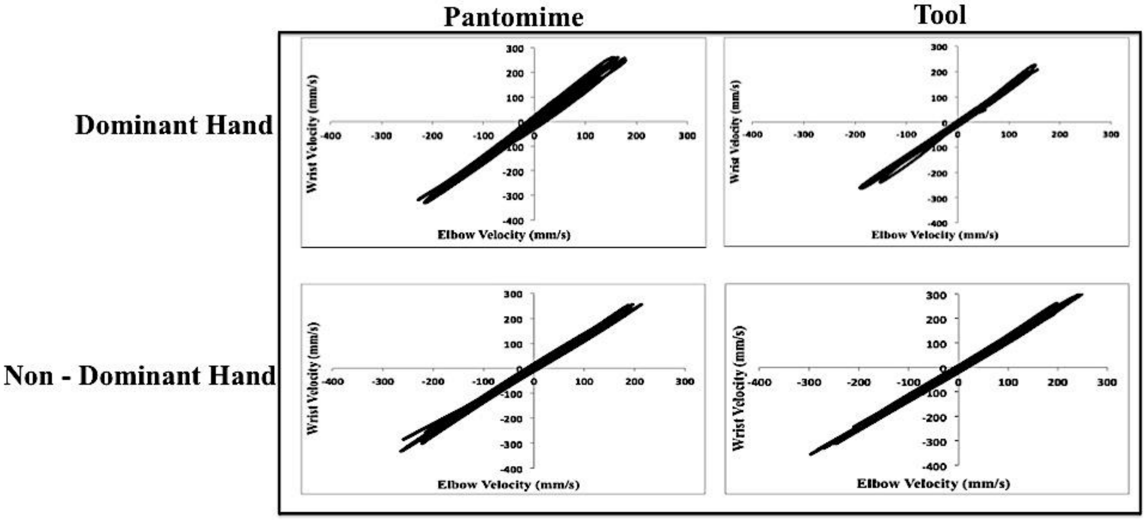


Figure 21: Kinematic relationship between elbow velocity and wrist velocity in pantomime and tool conditions for dominant and non-dominant hands in younger adult. This example is for one trial only.

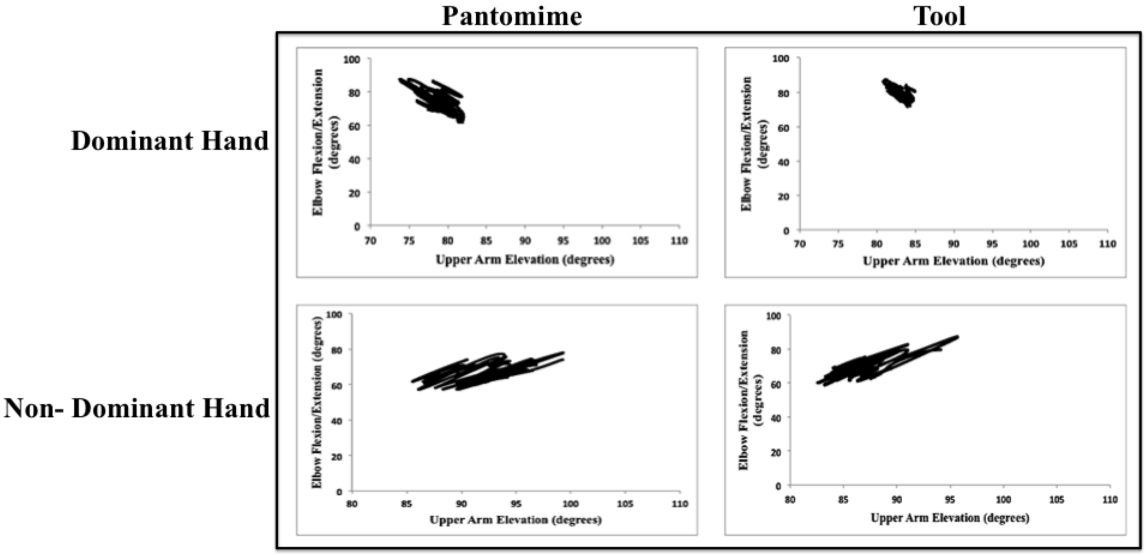


Figure 22: Kinematic relationship between joint angles (shoulder and elbow) in pantomime and tool conditions for dominant and non-dominant hands in older adult. This example is for one trial only.

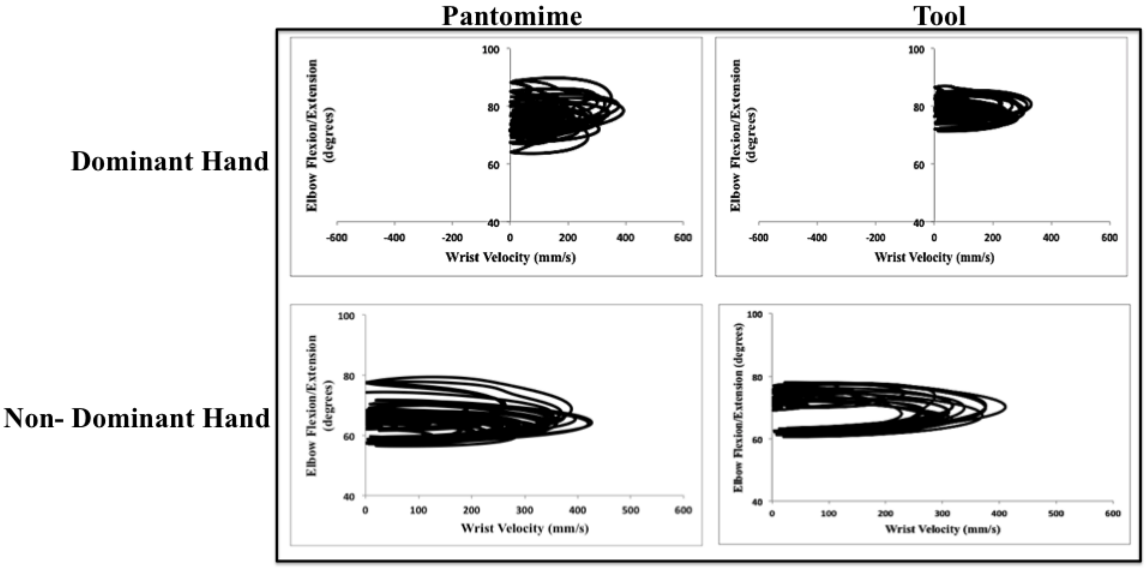


Figure 23: Kinematic relationship between elbow flexion/extension and wrist velocity in pantomime and tool conditions for dominant and non-dominant hands in older adult. This example is for one trial only.

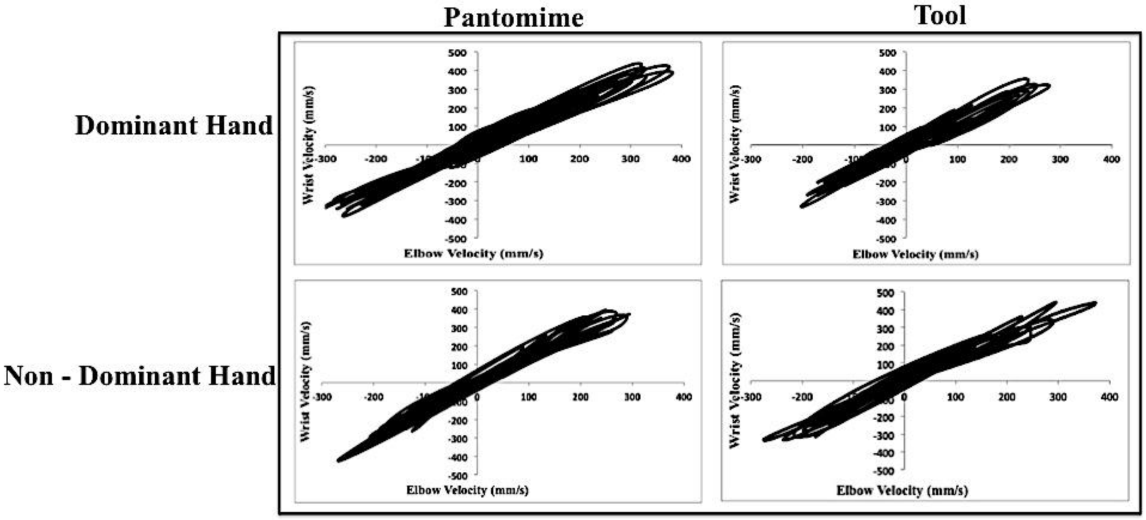


Figure 24: Kinematic relationship between elbow velocity and wrist velocity in pantomime and tool conditions for dominant and non-dominant hands in younger adult. This example is for one trial only.

9.3.1. Linear wrist and elbow velocity

Table 7 presents the Z-scores for each group, hand and task condition for relationship between linear wrist and elbow velocity. Statistical analyses revealed a main effect of age [F(1,30) = 9.0, *p* = .005], where overall older adults had lower Z scores relative to younger adults (OA: 2.57; YA: 2.90). Further, a significant main effect of condition existed [F(1,30) = 9.9, *p* = .0037], where the tool condition had a higher Z score relative to the pantomime condition (tool: 2.8; panto: 2.67).

Table 7: Z Scores for correlations between linear wrist and elbow velocities for task conditions and hands in younger and older adult groups.

Group	Hand	Pantomime	Tool
Younger Adults			
	Dominant	2.85	2.98
	Non-Dominant	2.78	3.01
Older Adults			
	Dominant	2.49	2.59
	Non-Dominant	2.59	2.65

The distribution of the slopes of regression of wrist against elbow velocities in the dominant and non-dominant hands during the performance of pantomime and tool conditions for all subjects (including the outliers) is presented in Figures 25 and 26. The left hand panels represent slopes for movement in the pantomime condition, while the right-hand panels display slopes for movement in the tool condition. The top figures are for the dominant hand, while the bottom figures are for the non-dominant hand. The slopes of the younger adults ranged between 0.9 to 1.5 when pantomiming the slicing gesture with the dominant hand. Likewise, slopes of younger adults actually manipulating a tool ranged between 0.9 to 1.7. Thus, the presence of the tool improved performance in some younger adults, as scores for the tool condition tended to cluster around 1.1. In comparison, slopes of older adults for the movement with the dominant arm in pantomime condition ranged between 1 to 1.5. In tool condition, the slopes clustered between 1 and 1.3.

In terms of non-dominant arm performance, slopes for younger adults in pantomime clustered between 0.9 and 2.2. Once the tool was introduced, the range for slopes was between 1 and 1.5, with majority of participants having slopes clustered around 1.2. In older adults, for pantomime condition, the non-dominant arm slopes were between 1.1 and 1.5. However, once the tool was present, slopes ranged between 1.1 and 1.3.

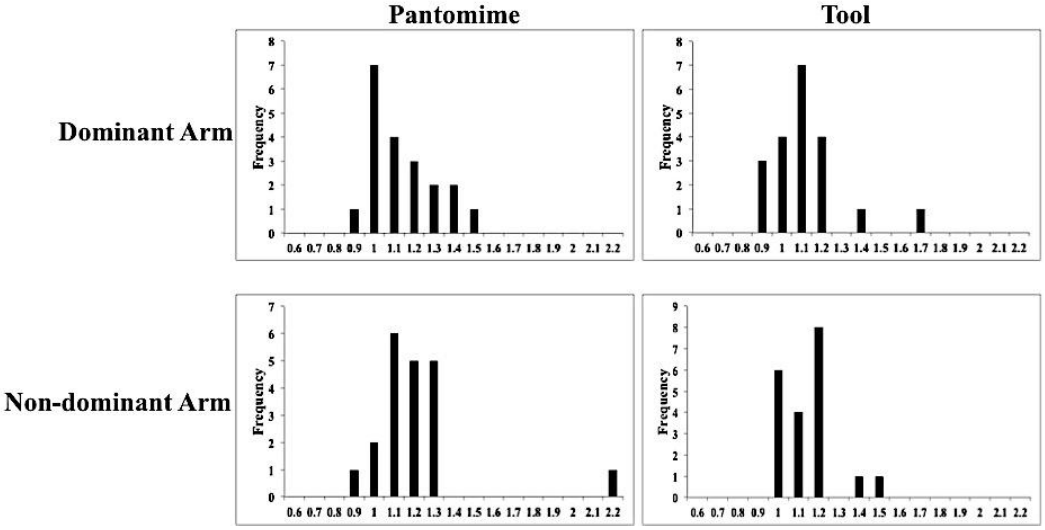


Figure 25: Slopes between wrist and elbow velocities for all younger adult participants in pantomime and tool conditions.

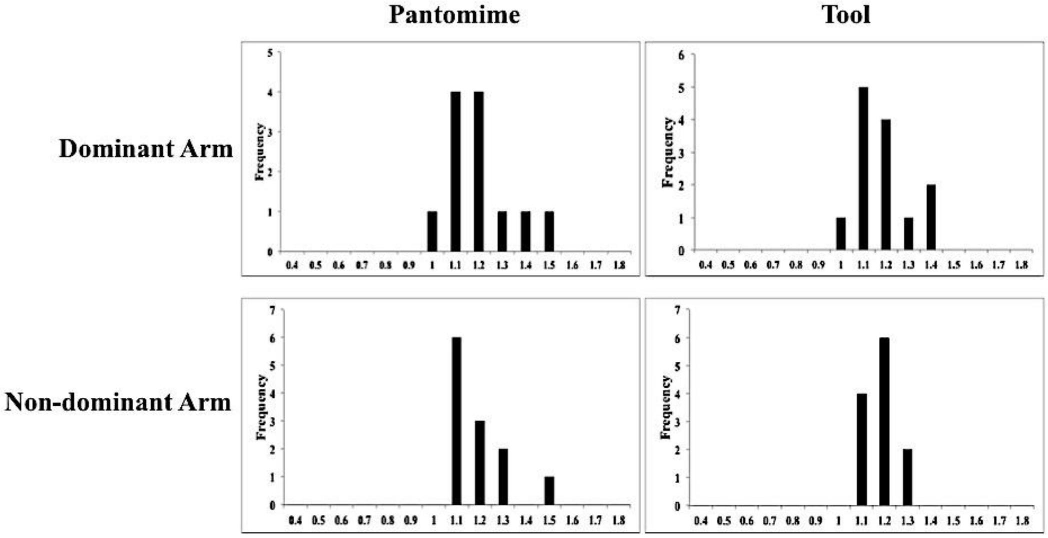


Figure 26: Slopes between wrist and elbow velocities for all older adults participants in pantomime and tool conditions.

9.3.2. Elbow Flexion/Extension and Linear Wrist Velocity

Statistical analyses revealed a main effect of hand [F(1,30) = 4.66, *p* = .03] and condition [F(1,30) = 23.4, *p* < .0001]. The non-dominant arm had higher RMSE (ND: 391.7; DM: 345.6). Further, pantomime condition had a higher RMSE in comparison to tool (panto: 417; tool: 320.4). Further, a 3-way interaction was found between hand, age and condition [F(1,30) = 8.4, *p* < .0068]. In the pantomime condition, no differences existed between the two age groups for the dominant limb in terms of RMSE (panto YA: 407; panto OA: 409). However, differences in the two age groups existed for the non-dominant limb in the pantomime condition. Older adults had a lower RMSE relative to the younger adults (panto YA: 477; panto OA: 375). In the tool condition, younger adults had a higher RMSE relative to older adults in the dominant limb (YA tool: 307; OA tool: 260). For the non-dominant limb, the RMSE score was similar between the two groups (YA tool: 348; OA tool: 367). Overall, RMSE scores were higher in the non-dominant limb relative to the dominant limb for both groups and both conditions.

In terms of shape of the ellipse, significance was only found for age [F(1,30) = 7.4, *p* = .01]. Older adults had lower wrist velocity (ratio: 28), while younger adults had larger wrist velocity (ratio: 37).

Figures 27 and 28 depict an example of a best-fit ellipse for a younger adult and an older adult respectively in pantomime and tool conditions for both limbs.

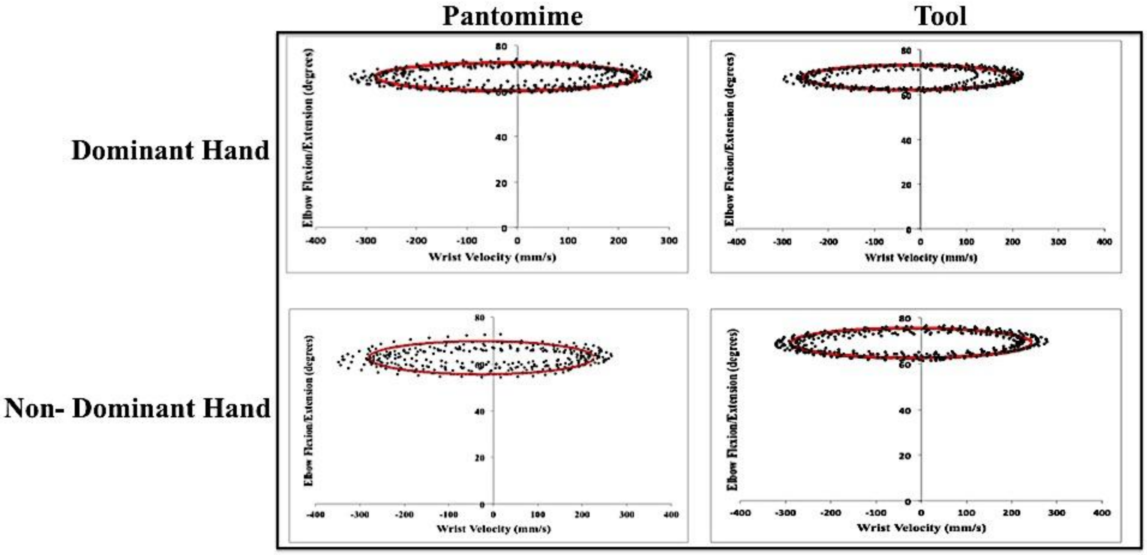


Figure 27: Best fitting ellipse for the relationship between elbow flexion/extension and wrist velocity in pantomime and tool conditions for dominant and non-dominant hands in younger adult. This example is for one trial only.

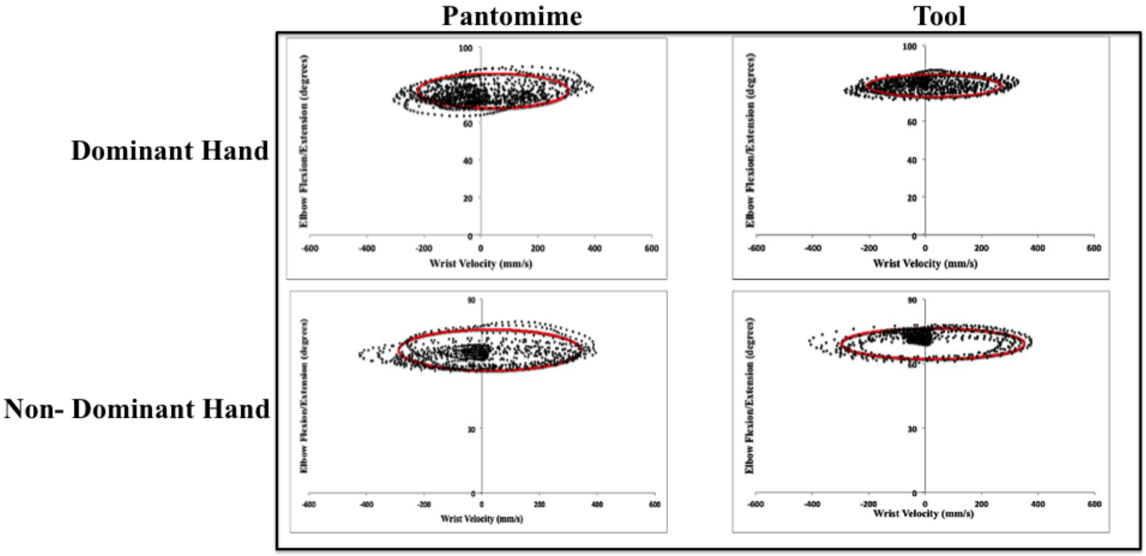


Figure 28: Best fitting ellipse for the relationship between elbow flexion/extension and wrist velocity in pantomime and tool conditions for dominant and non-dominant hands in older adult. This example is for one trial only.

10.0 Discussion

This thesis project set out to investigate the influence of aging on manual asymmetries in different task conditions as it pertains to apraxia assessment. To achieve this objective, manual asymmetries were examined in a group of younger and older adults during the performance of two daily tasks in pantomime and tool conditions: drinking water from a cup and slicing an imaginary loaf of bread with a knife. Research to date has concentrated on the investigation of manual asymmetries during constrained reaching movements, reach-to-grasp movements, aiming and pointing. However, very little research has been dedicated to examining manual asymmetries in the context of tool use and the impact of aging on dominant and non-dominant arm movements in these tool-use tasks. Assessment of apraxia involves tool use movements, but it does not adequately take into consideration motor lateralization when performing ADLs. The current study addresses motor lateralization in healthy younger and older adults in hopes of shedding some light on how aging, lateralization, and different task conditions play a role in the performance of naturalistic movements.

10.1. Manual Asymmetries and Aging Affect Motor Performance on the Grooved Pegboard Task

The present investigation shows that aging and manual asymmetries affect both tasks (place and remove) in the Grooved Pegboard. The place task is a visual-motor test, which requires a great deal of manual dexterity and precision to place the pegs into the holes at the highest speed and accuracy. Contrastingly, the remove task is more of a motor speed test, requiring less precision (Bryden et al., 2005). In this study, aging significantly contributed to slowing down of the motor performance during place and remove tasks. This is consistent with previous studies, which examined Grooved Pegboard performance in older adults (Ranganathan et al., 2001; Mithrushina et al., 1995; Ruff et al., 1993). Ranganathan et al. examined the place task of the Grooved Pegboard in 27 younger and 28 older adults. They found that older adults needed 29% more time than younger adults to complete the task. Further, Ruff et al. examined the performance on Grooved Pegboard and Finger Tapping tasks in younger and older adults (1993). He found that increasing age is associated with an increase in movement time in the Grooved Pegboard task. Tactile information of the hand and fingers is fundamental for tool manipulation, grasping and overall manual dexterity (Johannson, 1996). With aging, the ability to process tactile information declines, impairing fine motor control (Kinoshita et al., 1996; Lazarus et al., 1997). Due to this, older adults had substantially more difficulty manipulating the pegs and placing them in the holes, as well as removing them from the holes.

Differences between the hands were also quantified during the performance of the Grooved Pegboard task. The non-dominant hand in both groups was slower at completing the place and remove task. Research to date has shown that non-dominant limb performance is slower in comparison to dominant limb on both tasks (Bryden et al., 2005; Mithrushina et al., 1995). Bryden et al. (2005) investigated the performance of place and remove tasks in a group of younger adults. They found that the dominant hand is 8s faster for the place task and 1 second faster on the remove task relative to the non-dominant limb. This investigation found comparable results, in that the dominant limb was 4.67s seconds faster in the place task and 1.01 seconds faster in the remove task in comparison to the non-dominant limb. Further, in this study, laterality quotient for place task was 4.09 and for remove task was 2.32 for young adults. In this case, laterality quotients reveal that the hand differences are larger in the place task relative to the remove task, consistent with previous studies (Bryden et al., 2005; Bryden et al., 1999). While overall differences between hands in older adults were comparable to that of younger adults – dominant hand was 4.29 seconds faster in the place task and 1.86 seconds faster in the remove task - laterality quotients for place and remove task for older adults did not follow this pattern. Laterality quotient for the place task was 3.05 and for the remove task was 3.41. Thus, differences in limb performance increased in older adults for the place and remove tasks. Larger differences in terms of a laterality quotient for the place and remove tasks quantified in older adults may point to a disruption in visuomotor control and motor speed respectively (Bryden et al., 2005).

Correlations between performance measures and preference in this study were not consistent with the previous findings. While the performance on remove task in younger adults had moderately significant correlation with the scores on the WHQ in Bryden et al.'s study (2005) and strong correlations between WHQ scores and place task in Brown et al.'s study (2006), no significant correlations were found between performance and preference measures in either of the groups. However, this study had significantly lower sample size relative to the two previous studies. Smaller sample size may have impacted these findings.

10.2. The effect of Manual Asymmetries on ADL Performance

Manual asymmetries are elicited during the performance of the cup and knife ADLs. In the cup ADL, manual asymmetries emerge in peak velocity towards the mouth, as well as TPV and TAPV away from the mouth. Specifically, it was found that when individuals raised the cup towards the mouth, higher peak velocities were achieved in the non-dominant limb regardless of age. This is contrary to the previous research on manual asymmetries in reach-to-grasp movements, which has consistently found that the dominant arm achieves higher peak velocities relative to the non-dominant arm (Annett et al., 1979; Boulinguez et al., 2001; Roy et al., 1994). Key differences between this study and the previous research might explain these contradicting findings. The results depicted in this document pertain to actual use of tools, while previous studies have examined temporal and spatial measures in terms of reaching or pointing movements. Research which has quantified peak velocities in dominant and non-dominant limbs during the performance of ADLs have mostly investigated patients with limb apraxia. In a study by Hermsdorfer et al. (2013), it is evident that the non-dominant limb of the controls had a slightly higher peak velocity during a hammering movement relative to the dominant limb in both task conditions. Hence, it may be that the non-dominant limb has reduced ability to control the movement and scale peak velocity when nearing a target. Although the non-dominant arm is often used to drink from a cup (ie. the frequency of picking up a cup and drinking from it with both hands is high), it is less skilled than the dominant arm and may not have a well-developed strategy to reduce the speed of movement. The task of drinking from a cup requires the arm to accelerate towards the mouth, reach peak velocity and then decelerate to halt the movement prior to reaching the mouth. Hence, having a higher than optimal peak velocity would cause the participant to miss the mouth and spill water. Therefore, the dominant arm, being highly specialized for trajectory formation (Sainburg, 2002), is able to scale this peak velocity so that the final goal can be achieved successfully.

Hand differences also emerge in terms of temporal aspects of movement – time to peak velocity and time after peak velocity. The dominant limb spends slightly more time to reach peak velocity, while the non-dominant arm spent longer time after peak velocity in the second cycle of movement (ie. lowering the cup towards the table). There are two potential possibilities of why this is the case. Firstly, it could be due to the ability of the right hand/left-hemisphere system to achieve an appropriate motor response with less information on which to base corrections (Roy et al., 1994; Lavrysen et al., 2007). Hence, the non-dominant arm would make trajectory corrections, which would in turn, increase the time in deceleration. Secondly, more recent research has shown that the non-dominant arm displays errors in movement direction and curvature, which are consistent with failure to predict the effects of gravity (Tomlinson et al., 2012). In this cycle of movement, participants were required to lower the cup towards the table. Hence, the inertial or gravitational effects should have been accounted for during on-line control of movement. In general, during unsupported reaching tasks, such as the ones performed in daily tasks, the motor system must accurately take into consideration the effect of gravity on the movement, as well as accurately account for this gravity to execute a desired movement (Tomlinson et al., 2012). Non-dominant limb has increased initial direction errors in movement (Tomlinson et al., 2012). Longer time after peak velocity quantified in the non-dominant limb can be due to the non-dominant limb's reliance on a feedback mediated controller, and thus, in the process, its failure to compensate for gravitational effects.

Higher peak velocities, shorter time to and longer time after peak velocity in the non-dominant arm were coupled with lower range of motion at the shoulder, elbow and the wrist. Using a cup to drink water is a highly constrained task and requires the coordination of three joints to act in unison. In 1967, Bernstein proposed that to be able to master a specific task, one must be able to control for multiple and redundant degrees of freedom involved in that task. Vereijken et al. (1999) hypothesized that to tackle the initial complexity of the task, a person must "freeze" joints and thus limit the degrees of freedom required. This ultimately means that the learner will lock certain joints and thus, have a whole limb segment operate as a unit. It follows then that as the improvements in acquiring a skill increase, a person will progressively release degrees of freedom, coordinating and controlling skillfully an increasing number of degrees of freedom. The decreased range of motion seen at each of the joints of the non-dominant limb in this study during the cup ADL suggests that the non-dominant arm system was acting as a novice trying to learn the task at hand. A system that is more skillful at the task, such as the dominant hand system, will, in opposition, have an increased range of motion at each of the joints initially. In a study by Newell et al. (1989), participants were asked to sign a piece of paper with both their dominant and non-dominant hands. They showed that when participants signed with the dominant arm every joint was involved as depicted by higher correlations between the joints. In the current study, lower cross correlations between wrist, elbow and shoulder indicated that the joints were not controlled independently (see page 15 for discussion on interjoint coordination).

In the knife ADL, differences between the hands were present in terms of time to peak velocity and cycle duration, but not in terms of time after peak velocity. The non-dominant limb took longer to reach peak velocity and thus, each cycle of movement was longer relative to the dominant limb. Upon closer examination of the data, it was found that manual asymmetries in both conditions were only present in older adults. On the contrary, no manual asymmetries were quantified in younger adults. This agrees with previous findings by Heath et al. (2002), who found that movement deceleration, which reflects feedback processing, was not different between the hands in younger adults. Participants in the current study performed slicing gestures in both pantomime and tool, without the object (i.e. loaf of bread) present. Thus, accuracy, precision and terminal constraints were not as high as they would have been if the ADL was performed in the presence of an object. The fact that the deceleration phase did not yield any differences between the hands is not surprising, as the visual target (i.e. loaf of bread), which helps in generation of online movement corrections, was not physically present during the movement (Heath et al., 2002). The time to peak velocity in tool use phase, on the other hand, may reflect a combination of planning and feedback processing. In this case, it is possible that dominant limb spends more time to reach peak velocity to better plan and organize a movement, hence spending less time after peak velocity to correct for movement errors.

Interestingly, Bernstein’s theory on degrees of freedom did not hold true for the knife ADL. In fact, for shoulder elevation and shoulder plane of elevation, the non-dominant arm produced higher range of motion relative to the dominant arm. This is a rather interesting finding, as one would also expect to observe freezing of the joints in the knife ADL similarly to the cup ADL. The knife ADL is slightly less constrained relative to the cup ADL, and requires a significant amount of control amongst the three joints. Further, this movement is mostly characterized by elbow flexion/extension, coupled with shoulder elevation and flexion (Poizner et al., 1995). In this study, both, the dominant and non-dominant limb achieved a similar range of motion at the elbow, but the non-dominant limb used much more shoulder elevation and forward flexion than the dominant arm. The non-dominant arm is typically characterized as better suited for stabilization of objects or postural orientation tasks, where the trajectory is not fundamental to complete the task (Sainburg, 2002). It does not, therefore, need to acquire higher intersegmental dynamics. This could be due to a less effective control of intersegmental dynamics in non-dominant limb. Hence, the non-dominant limb utilized the shoulder substantially more relative to the dominant limb to control the movement at the elbow and the wrist. It follows then that the joints in the non-dominant limb may have not acted in unison, but rather there was a divergence in the control of movement at the shoulder relative to the wrist and elbow. It is likely that, to better control the movement during the slicing gesture in the non-dominant arm, participants relied primarily on the shoulder.

10.3. The Effect of Aging on ADL performance

Aging contributed to overall slowing of performance in both ADLs as quantified by lower peak velocities, longer time to and time after peak velocity, as well as prolonged cycle duration in the older adult group. Neuromuscular changes with age may explain some, but not all of the differences in movement between the two groups. Birren et al. (1980) suggested that physical factors such as degeneration of the central nervous system processes may contribute to general age-related slowing and impact motor function. Diggles-Buckles (1993) found that older adults have slower movement relative to younger adults. They found that movement slows down with age by as much as 15-30%. In the current study, movement in older adults slowed down between 20-27% in both ADLs. However, this does not come at the expense of completing the task. All older adults who participated in this study successfully completed both of the tasks. It could be that older adults emphasized precision in movement rather than its speed (Bellgrove et al., 1998). However, precision was not evaluated in the current study.

Older adults had substantially lower peak velocities in cup ADL. This is in accordance with previous research which has found that older adults produce movements with up to 30-70% lower peak velocity relative to young adults (Ketcham et al., 2002; Bellgrove et al., 1998; Goggin et al., 1992). Lower peak velocities quantified in older adults may be the result of decreases in the amount of muscular force that can be generated (Vidt et al., 2012), as certain amount of muscle force is required to control the drinking movement. The cup ADL required increased precision to bring the cup to the mouth and then place it back on the "X". The fact that older adults performed this movement with less speed may indicate that older adults have slower online guidance when greater movement precision is required (Bellgrove et al., 1998).

Turning to the knife ADL, older adults had similar velocities to their younger adult counterparts. In a study by Cooke et al. (1989) which investigated the impact of aging on the performance quick and "own speed" elbow flexion movements, it was found that peak velocities did not significantly differ between younger and older adults. While there were no group differences in peak velocity older adults trended towards a relatively earlier temporal setting of peak velocity, which is consistent with the studies on reach-to-grasp movements and pointing movements. The length of the deceleration phase is related to the accuracy requirements of the task (Castiello et al., 1992; Marteniuk et al., 1987; Bennett et al., 1994). Hence, while older adults maintained similar peak velocities as younger adults, it was at a cost of overall movement time (e.g. longer cycle duration seen in older adults). The longer deceleration phase in older participants may reflect a more conservative movement strategy relative to younger adults and an increase in submovements required to complete the task (Bennett et al., 1994). In other words, older adults fail to terminate their movements at correct times and thus, require additional submovements to achieve a required movement precision.

10.4. Interplay of Manual Asymmetries and Aging

At the beginning of this study, it was hypothesized that aging will contribute to reduction in manual asymmetries during the performance of both ADLs. However, no significant results in temporal measures in terms of hand differences were found for cup and knife ADLs to support this hypothesis. In fact, the only result, which was significant for hand by age interaction, was in terms of time after peak velocity for the second cycle of movement in the cup ADL and towards the body peak velocity in knife ADL. A closer examination of data revealed that manual asymmetries were not present in younger adults, but were quantifiable in older adults. Relative to younger adults, both the dominant and non-dominant limbs of older adults had higher peak velocity in the knife ADL and longer time after peak velocity during the second cycle of movement in the cup ADL. In terms of time after peak velocity, the non-dominant arm of older adults took longer time for feedback processing relative to their dominant arm. This may be due to a greater age-related decline in the right hemisphere processing functions and is consistent with previous findings that have investigated more complex tasks, such as drawing and tracing triangles and have found increased manual asymmetry in older adults (Francis et al., 2000; Texeira et al., 2006).

Further, investigation into the effects of aging on manual asymmetries in terms of range of motion at the wrist, elbow and shoulder revealed once again that there is no reduction in manual asymmetries in older adults. For cup ADL, these asymmetries were particularly pronounced in older adults in terms of range of internal/external rotation, forearm pronation/supination, wrist radial/ulnar deviation and wrist flexion/extension. When comparing the performance of the two hands, younger adults only had slight differences in range of motion between the two limbs, relative to older adults. This was also the case for knife ADL, where manual asymmetries were more pronounced in older adults in terms of range of shoulder elevation and pronation/supination at the wrist.

It can be concluded that aging does not contribute to a reduction in manual asymmetries in cup and knife ADLs. According to results of this study, the opposite may be the case in that manual asymmetries were more pronounced in terms of some dependent measures in older adults relative to younger adults. This finding is consistent with the results found in Francis et al.'s (2000) and Teixeira et al.'s (2006) study on tracing and drawing tasks respectively, which found higher manual asymmetry in older as compared to younger adults. In this regard, it should be noted that the cup and knife ADLs, just like drawing, are highly practiced throughout the lifespan. As a child, one of the first tools a person comes into contact with is a cup and throughout lifetime and on a daily basis, people reach, grasp and use cups for drinking, pouring, etc. The same can be said about the knife. Knife ADL represents a highly skilled, learned movement and for the most part, people use the knife with their right hand. In this case, the cup ADL is used more frequently used with both hands. It is apparent that lifelong practice, which contributes to extensive motor experience, plays an important role in preserving the performance of an ADL with the practiced limb (in this case, the dominant arm). In contrast, the performance with the non-practiced or non-dominant limb declines with age (Texeira et al., 2006).

It should be noted that this study included a heterogeneous group of individuals with different degrees of handedness. A highly right handed individual as defined by the Waterloo Handedness Questionnaire may have a greater degree of asymmetry during the performance of these tasks relative to an individual whose degree of right-handedness is on a lower side of the spectrum.

10.5. Effects of Aging and Task Conditions on ADL Performance

Task conditions contributed to adjustments in peak velocities and joint ROM in both ADLs. Tool manipulation has been found to improve the production of transitive gestures (ADLs) in some apraxic patients (Clark et al., 1994; Hermsdorfer et al., 2006; 2011; Poizner et al., 1995, 1990). Improved performance resulting from the presence of a tool is due to the presence of somaesthetic and visual cues. In this study, performance of ADLs was evaluated in the context of two task conditions, pantomime and tool, to investigate whether the addition of only the tool (e.g. knife) generates adjustments in performance of ADLs in younger and older adults. The presence of the cup lowered peak velocities in both younger and older adults. Our findings support previous work on stroke patients and healthy controls involving the performance of ADLs in pantomime and tool conditions, which have found that pantomiming elicits higher peak velocities (Hermsdorfer et al., 2006; Poizner et al., 1995, 1990; Hermsdorfer et al., 2011; Hermsdorfer et al., 2013). In the knife ADL, the presence of the tool generated adjustment in peak velocities in younger adults. That is, higher peak velocities were generated in the pantomime condition. This was also found in Heath et al.'s study, which investigated the performance of knife ADL in healthy younger adults (2002). Exaggerated movements in pantomime serve to facilitate the understanding of the pantomimed gesture (Hermsdorfer et al., 2006; Laimgruber et al., 2005).

However, in older adults, no differences were found between the two task conditions. Since there is only one study that looked at differences between arms and conditions in healthy adults, but did not investigate this in older adults, we have to rely on control data from the apraxia research. Clark et al. looked at slicing with a knife gesture in 3 apraxic patients and 4 healthy older adults (1994). While the focus of Clark et al.'s study was not on differences in performance conditions, we can deduce from their results that the differences between pantomime and tool tasks for peak wrist velocity and movement time (or cycle duration) for the slicing gesture did not differ much. Since the object (i.e. bread) was not present in either of the studies, there was no need for precision or accuracy in movement as required when an actual loaf of bread is present. This means that the motor program generated in older adults when performing without a tool was not different from the one used when performing with the tool. Further, cutaneous sensibility declines as one ages (Sabin et al., 1984), impairing fine motor control. Due to this, older adults may not have scaled their peak velocities in the same way as younger adults. The presence of the tool only, thus, was not enough to elicit adjustments in temporal measures during the performance of knife ADL in the tool condition in older adults.

The tool condition in the cup ADL was also characterized by longer time after peak velocity and overall cycle duration for both cycles for the cup ADL. The slowing in movement quantified in the tool condition reflects the mechanical requirements and constraints of the task when partial somaesthetic cues were added and is consistent with the findings by Hermsdorfer et al. (2011). In pantomime condition, participants did not need to decelerate their movement as they approached their mouth or the table since the cup was not present in their hand. On the contrary, the tool condition required the participants to decelerate the movement in both directions so as not to hit the mouth or tip over the cup as they placed it back on the table. This increased need for precision in the tool condition, in turn, increased the time it took to perform the task.

Tool condition also elicited adjustments in range of motion at the shoulder, elbow and wrist. In terms of both cup and knife ADL, range of shoulder elevation increased in older adults in the tool condition relative to the pantomime. However, there were no differences in terms of shoulder elevation in younger adults between the two conditions. This supports some of the previous findings that tool condition may produce higher range of movement at the joint. Drawing from the results by Hermsdorfer et al. (2013), it can be seen that the amount of wrist movement increased in tool condition (or demo as they called it in the study) relative to the pantomime condition in hammering ADL. This was particularly the case in terms of the wrist joint for knife ADL in the present study, where range of radial/ulnar deviation, pronation/supination and flexion/extension was higher in older adults during the tool condition relative to the pantomime condition. These adjustments were not present in younger adults. It can be concluded based on these results that despite the fact that the cup did not have water in it and there was no requirement to slice an actual loaf of bread, older adults put more emphasis on performing the pantomime condition with higher precision.

10.6. Somaesthetic Influences on Hand in ADL Performance

Previous literature has suggested that the extent to which somaesthetic cues may influence adjustments in spatial, temporal and spatio-temporal aspects of movement in the dominant and non-dominant limbs may be different (Heath et al., 2002). In the present study, it was found that the degree to which the tool condition influenced performance was greater for the non-dominant limb for the knife ADL. In the knife ADL, peak velocities towards the body were substantially lower in the non-dominant limb in the tool condition relative to the pantomime and dominant limb. This was also the case for shoulder elevation, where range of motion was reduced in the tool condition for the non-dominant limb relative to the dominant limb. This is in accordance with previous findings by Heath et al. (2002) who have found that the degree of trajectory consistency was the greatest in the pantomime condition for the dominant limb, but this lessened in the tool condition. However, in the cup ADL, this was not the case, as somaesthetic cues seemed to influence the performance of the dominant limb substantially more. For time to peak velocity, it was found that it takes longer to reach peak velocity in the tool condition with the dominant limb. This could indicate that the left hemisphere/right limb system may be better at processing feedback information and planning in the pantomime condition relative to the non-dominant limb. Once the tool is introduced, the dominant limb takes longer time to process the feedback and plan for movement deceleration, hence limiting the number of corrective sub-movements necessary to change the direction of trajectory (e.g. start of second cycle of movement in cup ADL). Further, while adjustments in mean range of shoulder elevation are present in the dominant limb, this is not the case for the non-dominant. Hence, the presence of the tool does not constrain the range of motion at the shoulder in the non-dominant limb.

Although this interaction may indicate that the degree to which somaesthetic cues influence ADL performance may be dependent on the limb and the type of ADL (e.g. cyclical versus non-cyclical), the fact that this interaction was not present across all temporal, spatial and spatio-temporal measures indicates that caution should be used when interpreting this result. To fully understand to what degree somaesthetic cues influence ADL performance in both limbs, manual asymmetries should be evaluated across different contexts (e.g. object only present versus tool only present).

10.7. Interjoint Coordination in Healthy Populations

The typical movement profiles while performing a knife ADL presented in Figures 19 through 24 demonstrate that a successful performance of a slicing gesture requires precise temporal coordination of the shoulder and elbow movements. Top panels in Figures 19 and 22 present elbow flexion/extension plotted against upper arm elevation.

Figure 19 represents a movement exhibited in one trial of a healthy younger adult in pantomime and tool conditions, while Figure 22 is a kinematic profile for a healthy older adult.

As can be seen from the figures, both younger and older adults produced a slicing gesture that was smooth and for the most part linear. The gesture was characterized with sharp reversals from the backward and forward portions of the movement. However, obvious differences existed between the limbs, conditions, and groups. The dominant hand of younger adults in the pantomime (Figure 19 top left panel) produced larger ROM for upper arm elevation (approximately covered 10 degrees of upper arm elevation during the 7 slices) with more elbow flexion/extension. In contrast, the non-dominant hand had less upper arm elevation (Figure 19 bottom left panel) during pantomime condition. Once the tool was introduced, both the dominant (Figure 19 top right panel) and non-dominant limb (Figure 19 bottom right panel) had a more constrained movement, characterized by slightly lower ROM at the shoulder. Interestingly, the tool condition constrained the dominant limb movement more in a plane relative to the non-dominant limb. On the other hand, older adults produced movements with a lot less upper arm elevation in the dominant limb for both pantomime and tool conditions (Figure 22, top left and right panels) relative to younger adults. The non-dominant limb movements of older adults were characterized by larger upper arm elevation in both conditions (Figure 22, bottom left and right panels), but still less than that of a younger adult. Interestingly, in older adults, like in the younger adult group, the effect of tool could be seen more for the dominant limb, unlike the non-dominant limb. Overall, for the younger participant, the change from elbow flexion/extension to upper arm elevation occurred nearly synchronously in both conditions and it was characterized by a tight relationship between these two measures. However, in older adults, while this relationship was still linear, for each forward and backward portion of the slicing gesture, the ROM at a joint was reduced.

Most younger and older adults exhibit a very tight, linear relationship between speed at the elbow and speed at the wrist, particularly as it pertains to the tool condition. This has been documented in previous kinematic studies investigating interjoint coordination in healthy older adults and apraxic patients (Poizner et al., 1995). However, it should be noted that not all individuals perform this way. As can be seen from frequency analyses in Figures 25 and 26, some healthy younger and older adults fall in the slope range that is appropriate to that of an apraxic patient. In their study on interjoint coordination deficits in apraxic patients, Poizner et al. (1995) noted that slopes of the control subjects, which included only older adults, fell between 0.95 and 1.35 for the pantomime condition and 0.75 to 1.15 in the tool condition. On the other hand, apraxic patients produced movements in which the relationships between the wrist and elbow speeds were highly variable and ranged between 0.75 to 2.35 for pantomime and 0.55 to 1.35 for tool condition. A couple of participants in this study performed below or above the range mentioned as the healthy control range in Poizner's study. For example, in the present study, one younger adult had a slope of 2.2 while pantomiming with the non-dominant arm. Hence, this raises a question of whether the impairments quantified in Poizner's study in apraxic patients were truly due to limb apraxia or whether these impairments may have already been present in the individuals studied. Statistical analyses on Z scores for wrist and elbow velocity also showed that younger adults had a higher interjoint synchrony relative to older adults, as was hypothesized.

It should be noted from Figures 21 and 24 that this relationship between speed at the elbow and speed at the wrist, while highly linear in both groups of adults, is also slightly different in older adults, as depicted by Z scores. In younger adults, each forward and backward stroke is tightly controlled in both dominant and non-dominant limbs and characterized by overlapping strokes (e.g. forward and backward movement of a second stroke is identical to that of the first stroke). This highly linear and coupled movement yielded high Z scores in younger adults, meaning high interjoint synchrony. However, older adults have a lot more variability as depicted in Figure 24 and based on a Z score. They cover a higher range of speed at the wrist and the elbow, relative to younger adults, as well as have lower Z scores.

Elbow flexion/extension is related to the speed at the wrist and represents a highly coupled parabolic relationship. In the present study, this relationship was investigated by looking at the RMSE, which quantifies the amount of variability during the movement, and shape of the ellipse created during the slicing gesture. As hypothesized, it was found that the non-dominant arm has a higher RMSE relative to the dominant arm. This means that the movement at the elbow and speed at the wrist are slightly more variable in the non-dominant arm, denoting less interjoint synchrony. This is to be expected, as the non-dominant limb system is not specialized for trajectory formation, but rather it is better suited for stabilization of objects (e.g. holding a loaf of bread) (Sainburg, 2002). Further, the pantomime condition was also associated with higher RMSE and thus, higher variability in movement. Once the tool was introduced, the movement became much more constrained as depicted by lower RMSE score. As discussed previously, the pantomime condition was not constrained, unlike the tool condition, in which the physical knife was present. Also, the object (e.g. loaf of bread) was not present during the tool condition. Hence, the demand for accuracy in the movement was not high in either the pantomime or the tool condition.

11.0 Clinical Relevance and Conclusion

The ultimate goal of this study was to investigate the effects of aging on manual asymmetries in different task conditions during the actual manipulation of the tool. This is only the second known study that quantified manual asymmetries in different task conditions during actual tool manipulation, and the first study to compare the performance of these tasks in healthy younger and older adults. This investigation, therefore, sheds light on how aging affects performance of ADLs, particularly pertaining to use phase of movement, manual asymmetries, as well as performance of two ADLs in different task conditions.

Limb apraxia is a disorder of skilled movement that impairs a person's ability to perform ADLs. Current assessment for limb apraxia involves gestural performance (ie. performance of ADLs) with the non-dominant limb to avoid hemiparesis of the dominant limb. Further, stroke patients are asked to gesture in two task conditions: pantomime and tool. The pantomime task is critical to assess integrity of the memory system that stores one's knowledge on how to perform an ADL, as well as the conceptual system (Stamenova et al., 2009). The tool task, on the other hand, has been shown to improve performance in apraxic patients, since the information about the tool (e.g. shape, size) is now available, making access to the specific action's motor program more attainable. This creates two visible problems with the current assessment. Firstly, the assessment does not adequately take into consideration that stroke patients are gesturing with their non-dominant arm. It is unknown whether the impairments the clinician is observing are due to limb apraxia or non-dominant limb use, especially in individuals who are defined as strongly right-handed according to the handedness questionnaires and performance measures (e.g. pegboard). Secondly, different task conditions (pantomime versus tool) may already influence ADL performance in healthy younger and older adults. However, whether this is the case and the degree to which it influences ADL performance in healthy populations is unknown.

In fact, previous research on healthy younger adults (Heath et al., 2002) has shown that ADL performance (i.e. slicing a loaf of bread with a knife) is dependent on which hand is used during performance of an ADL and in which task condition. More recently, Przybyla et al. (2011) have reported that manual asymmetries are reduced in older adults during the performance of motor tasks. If this is the case, there would be no need to include handedness of stroke patients in current neuropsychological assessment for limb apraxia. However, the current study indicates that aging does not contribute to a reduction in manual asymmetries during actual manipulation of tools in cup and knife ADLs. To the contrary, aging appears to increase the degree of manual asymmetry quantified in these two tasks, specifically as it pertains to changes in range of motion at the shoulder, elbow and wrist (e.g. range of motion covered during the performance of an ADL). This investigation did not evaluate whether and how the within participant degree of handedness impacts the performance of ADLs. It could be that individuals who are strongly right-handed according to the WHQ utilize different motor control to perform an action relative to individuals who fall at the lower end of the scale (e.g. mildly right-handed). Manual asymmetries may be greater when an ADL is performed with both tool and object present.

Further, previous research has shown that apraxic patients are impaired in pantomime and tend to improve their performance of the ADL once the tool or both, tool and object are present (Clark et al., 1994; Hermsdorfer et al., 2006; 2011; Poizner et al., 1995, 1990; Hermsdorfer et al., 2011). Clark et al. suggested that the presence of partial somaesthetic cues (e.g. addition of only the tool) would not substantially improve performance in apraxic patients (1994). This was confirmed by Hermsdorfer et al. (2013), who found that addition of partial somaesthetic cues during hammering ADL did not significantly improve performance. On the contrary, current investigation shows that even partial somaesthetic cues impact performance of ADLs in healthy groups. This agrees with previous findings on younger adults (Heath et al., 2002). However, upon closer examination of interjoint coordination, it should be noted that the degree to which each task condition impacted performance of an ADL may be dependent on within subject differences between the hands and thus, within subject differences in performance of ADLs in different task conditions should be taken into consideration when assessing for limb apraxia. For example, in this study, the presence of a tool improved performance of a knife ADL for some individuals, while others either did not benefit from the presence of the tool or the tool itself impaired performance.

The current study was limited to two specific tools: cup and knife. It remains to be shown whether findings on these tools can be generalized to other cyclical and non-cyclical ADLs that may give further insight into the effects of aging, manual asymmetries and different task conditions on the performance of ADLs. Needless to say, there is a great need to continue studying the effects of aging, manual asymmetries and task conditions in healthy younger and older adult groups during the performance of daily tasks. Currently, there is a lack of normative kinematic profiles for ADL performance in healthy younger and older adults. Development of these profiles would give insight into motor lateralization, motor control of upper limb in different task conditions, and effects of aging, all of which may need to be taken into account when assessing for limb apraxia after a stroke. Kinematic relationships presented in this study provide researchers and clinicians a single reference for normative kinematic profiles during the performance of one cyclical and non-cyclical task. In order to understand limb apraxia, it is important to understand how praxis changes across the lifespan for both limbs.

12.0 Limitations

The study had several limitations. The kinematics of specific ADLs investigated in this study were examined in a controlled environment. Participants may perform these same ADLs differently in a more familiar environment, thus altering the quantified kinematic differences between different conditions and limbs. Moreover, movements of the knife ADL were not constrained in a particular plane. Participants were asked to perform the movement as they would perform it in their home, increasing the variability in the study. Since this study focused on evaluating kinematics of ADLs located in the clinical screening tool (Waterloo-Sunnybrook Apraxia Battery), in which movements are highly controlled, it would have been better to constrain the environment as it would have been during the evaluation.

It should be also noted that the two ADLs performed in this study did not have the object present (ie. there was no loaf of bread and no water in the cup). Hence, the kinematics of ADLs in the full context (tool and object) may be different from the results obtained in this study. Moreover, not all spatial characteristics of the movement were evaluated (e.g. plane of movement, amplitude of movement). Since most apraxic patients exhibit impairments in plane of movement, it would be fundamental to examine whether healthy younger and older adults consistently perform in the same plane of movement in both conditions.

13.0 Future Work

Future research investigating manual asymmetries during the performance of daily tasks should evaluate these in the context of both, the tool and the object. Although, in this study, the presence of manual asymmetries was found in some aspects of movement, the addition of an object (e.g. bread) may have elicited larger differences between dominant and non-dominant limbs. Manual asymmetries may also be task dependent, and hence should be evaluated in multiple activities of daily living in younger and older populations.

Further, it would be of interest to develop an appropriate method and analysis to evaluate the degree of manual asymmetry within an individual, as differences between limbs within a stroke patient may be of greater importance when evaluating for limb apraxia. This can also be applied to different conditions. Pantomime and tool conditions may elicit differential changes in movement within a person. For example, while in some people tool condition may improve performance, in others this may not be the case. Since it has been shown that apraxic patients change the plane of movement when the tool and/or object are present, it would also be interesting to evaluate changes in spatial aspects of movement in healthy older and younger adults. All of these combined would lead to a more objective assessment of limb apraxia.

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APPENDIX A: Informed Consent Forms

In Search of Manual Asymmetries in Aging during Performance of Activities of Daily Living: Does Upper Limb Performance Become More Symmetric with Age?

Information Letter (Healthy Older Adults)

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You are invited to participate in a study entitled **"In Search of Manual Asymmetries in Aging during Performance of Activities of Daily Living: Does Upper Limb Performance Become More Symmetric with Age?"**. I am a Graduate Student in Kinesiology at the University of Waterloo. As part of my research project, I am conducting a study that examines dominant and non-dominant upper limb motor control during activities of daily living in healthy individuals. Before you agree to take part in this study, however, it is important for you to understand what you will be asked to do. The information below is given to help you to make a decision about whether or not you wish to participate.

What is the purpose of this study?

The purpose of this study is to investigate the differences in dominant and non-dominant limb motor control in healthy younger and older adults during the performance of activities of daily living (ADLs). Stroke causes paralysis of the upper limb and in some cases a disorder called apraxia. Apraxia is characterized by inability to perform ADLs, such as using a knife to slice a loaf of bread. Currently, neuropsychological assessment of apraxia, involves assessment of the non-dominant limb use. However, the assessment itself does not take this into consideration. Therefore, it is unknown whether impairments that are observed in neuropsychological assessment are due to apraxia itself or non-dominant limb use. While differences between dominant and non-dominant limb use have been investigated in simple tasks, such as pointing and aiming, in both younger and older adults, very little research has been dedicated at looking at these differences in ADLs in the context of aging. It is our hope that this study will provide us with more insight into the control of dominant and non-dominant limb use and therefore, help in enhancing the objectivity of initial assessments of apraxia.

Why am I being asked to participate?

You are being asked to participate in this study because you are a person 65+ years old and have met our inclusion criteria. Our inclusion criteria includes:

- *right-hand dominant*
- *no neurological or physiological disease/disorder of the upper limb (ex. Stroke or carpal tunnel syndrome)*
- *no history of concussion or brain trauma*
- *no upper limb or lower back injury within the past 6 months*
- *no blindness or visual problems that cannot be corrected for*
- *did not have shoulder surgery or endoprosthesis*

Your participation will help us gain a better understanding of the effects of aging on motor programming and motor control of dominant and non-dominant upper limbs, differences in the use of dominant and non-dominant limbs, as well as differences in upper extremity movements in younger and older healthy adults.

What will I be asked to do?

As a participant in this study, you will be asked to complete the Waterloo Handedness Questionnaire that will determine which is your preferred hand. You will also be asked to perform a pegboard task. You will be asked to put the pegs into the holes and take them out of the holes first with your preferred hand and then with your non-preferred hand. This will be timed by one of the researchers. The night before the study and the day of the study, you will be asked not to moisturize your hands, arms and trunk due to the sensitivity of the motion capture system.

Prior to participating, you will be asked to wear a tight spandex sleeveless white shirt provided to you by the student researcher to eliminate any artificial movements that result from your normal clothes. You will be seated at a table, surrounded by 8 Vicon cameras. To measure performance, 30 special markers will be affixed to your hand, wrist, forearm, elbow, shoulder and trunk with hypoallergenic medical-grade, double-sided adhesive tape, so that our motion analysis system can pick up the fine details of your reaching, grasping and any other movements you will perform. You will then be asked to do a couple of tasks from the Waterloo-Sunnybrook Apraxia Battery such as picking up an object and putting it down in the same location and pantomiming an activity of daily living from the battery.

In addition, you will be asked to provide some background information about yourself, such as age, gender, height and weight. You may also be asked some questions about your health history.

Where will the study take place?

The study will take place in the Ergonomics Laboratory (BMH 1404) at the University of Waterloo, Waterloo, Ontario.

How long will the study take?

The study will take approximately 2 hours to complete.

Can I change my mind about participating?

Participation in this study is voluntary. You are free to withdraw from the study at any time by advising the researcher, and may do so without any penalty.

Are there any risks involved in participating in this study?

Due to the repetitive nature of the reaching and grasping task over trials, you may experience restlessness or loss of attention for the task at hand. As such, optional breaks will be offered every 25-30 minutes during this task. Also, although minimal-to-no risks are anticipated, should you require a break for any reason at any other time, you can simply notify the researcher and the testing can be paused.

Are there any benefits to participating in the study?

There are no direct personal benefits to participating in the study. However, your participation in this research may help quantify dominant and non-dominant limb movements and determine kinematic profiles, which may be applied to individuals suffering from stroke and apraxia. This study will also help us quantify upper extremity motor control during certain activities of daily living. More specifically, it is our objective that the findings from our study be used to direct future research aimed at developing and enhancing tests that can be administered in clinical settings to diagnose and treat apraxia and stroke.

Will any remuneration be provided for my participation in the study?

There is $20 remuneration for participating in this research project. If you decide to withdraw partway through this study, you will be remunerated $20. You will also be provided with a parking pass.

Confidentiality and Security of Data

All information obtained in this study is considered completely confidential. Your name will not be included or in any other way associated, with the data collected in the study. Furthermore, because the interest of this study is in the average responses of the entire group of participants, you will not be identified individually in any way in any written reports of this research. Data collected during this study will be retained indefinitely, in a locked filing cabinet in a locked office in the BMH building, to which only researchers associated with this study have access. Electronic records of your performance will be stored in a similar secure manner without reference to your personal identity. These records will be stored on a computer disk with a unique password that can only be accessed by the researchers involved in the study.

If you decide to withdraw from the study during the experimental protocol, your data will be encrypted with a unique password known only to researchers and questionnaires will be kept locked in a filing cabinet in the office in the BMH building. The data and the questionnaires will remain confidential and will not be used in data analysis or any other research related purposes.

Who can I contact if I have any questions?

If you have any questions or concerns, please do not hesitate to contact me at (519) 888-4567 ext.32972 or tlulic@uwaterloo.ca for further clarification.

I would like to assure you that this study has been reviewed and received ethics clearance through the Office of Research Ethics at the University of Waterloo. However, the final decision about participation is yours. If you have any comments or concerns resulting from your participation in this study, please contact Dr. Eric Roy at (519) 888-4567 ext. 33536 or Dr. Clark Dickerson at (519) 888-4567 ext. 37844.

Consent:

If you agree to participate in this study, please read and sign the attached consent form. Thank you for your interest in our research and for your assistance with this project.

Sincerely,

Tea Lulic, Graduate student

Department of Kinesiology

University of Waterloo

Waterloo, Ontario, N2L 3G1

IN SEARCH OF MANUAL ASYMMETRIES IN AGING DURING PERFORMANCE OF ACTIVITIES OF DAILY LIVING: DOES UPPER LIMB PERFORMANCE BECOME MORE SYMMETRIC WITH AGE?

Consent Form

I, ____, the undersigned, agree to participate in this study being conducted by Tea Lulic of the Department of Kinesiology at the University of Waterloo under the supervision of Professor Eric Roy and Professor Clark Dickerson. I have made this decision based on the information I have read in the Information Letter and have had the opportunity to receive any additional details I wanted about the study.

I agree to participate in the study with the understanding that:

1. I may withdraw from the study at any time by telling the researcher without penalty
2. I may request that all my data and performance records be withdrawn and destroyed at a later date; and
3. My personal identity will remain confidential.

I was informed that this project has been reviewed and has received ethics clearance through the Office of Research Ethics (ORE) at the University of Waterloo. I may contact this office if I have any concerns or comments resulting from my involvement in the study by contacting the Director of the ORE (Dr. Maureen Nummelin) at the University of Waterloo (519-888-4567, Ext 36005; maureen.nummelin@uwaterloo.ca)

____

Name of Participant:

____ __________________

Signature of Participant: Date

____

Name of Investigator/Witness

____ ____________________

Signature of Investigator/Witness Date

In Search of Manual Asymmetries in Aging during Performance of Activities of Daily Living: Does Upper Limb Performance Become More Symmetric with Age?

Information Letter (Healthy Younger Adults)

University of Waterloo

October 29th, 2012

Student Investigator: **Tea Lulic**
Department of Kinesiology, Graduate Student
Email: tlulic@uwaterloo.ca

Principal Investigator: **Dr. Eric Roy**
Department of Kinesiology
Email: eroy@healthy.uwaterloo.ca

Dr. Clark Dickerson
Department of Kinesiology
Email: clark.dickerson@uwaterloo.ca

You are invited to participate in a study entitled **"In Search of Manual Asymmetries in Aging during Performance of Activities of Daily Living: Does Upper Limb Performance Become More Symmetric with Age?"**. I am a Graduate Student in Kinesiology at the University of Waterloo. As part of my research project, I am conducting a study that examines dominant and non-dominant upper limb motor control during activities of daily living in healthy individuals. Before you agree to take part in this study, however, it is important for you to understand what you will be asked to do. The information below is given to help you to make a decision about whether or not you wish to participate.

What is the purpose of this study?

The purpose of this study is to investigate the differences in dominant and non-dominant limb motor control in healthy younger and older adults during the performance of activities of daily living (ADLs). Stroke causes paralysis of the upper limb and in some cases causes a disorder called apraxia. Apraxia is characterized by inability to perform ADLs, such as using a knife to slice a loaf of bread. Currently, neuropsychological assessment of apraxia, which arises due to a left-hemisphere stroke and involves an inability to perform ADLs and gestures, involves assessment of the non-dominant limb use. However, the assessment itself does not take this into consideration. Therefore, it is unknown whether impairments that are observed in neuropsychological assessment are due to apraxia itself or non-dominant limb use. While differences between dominant and non-dominant limb use have been investigated in simple tasks, such as pointing and aiming, in both younger and older adults, very little research has been dedicated at looking at these differences in ADLs in the context of aging. It is our hope that this study will provide us with more insight into the control of dominant and non-dominant limb use and therefore, help in enhancing the objectivity of initial assessments of apraxia.

Why am I being asked to participate?

You are being asked to participate in this study because you are a person between 18 and 30 years old and have met our inclusion criteria. Our inclusion criteria includes:

- *right-hand dominant*
- *no neurological or physiological disease/disorder of the upper limb (ex. Stroke or carpal tunnel syndrome)*
- *no history of concussion or brain trauma*
- *no upper limb or lower back injury within the past 6 months*
- *no blindness or visual problems that cannot be corrected for*
- *did not have shoulder surgery or endoprosthesis*

Your participation will help us gain a better understanding of the effects of aging on motor programming and motor control of dominant and non-dominant upper limbs, differences in the use of dominant and non-dominant limbs, as well as differences in upper extremity movements in younger and older healthy adults.

What will I be asked to do?

As a participant in this study, you will be asked to complete the Waterloo Handedness Questionnaire that will determine which is your preferred hand. You will also be asked to perform a pegboard task. You will be asked to put the pegs into the holes and take them out of the holes first with your preferred hand and then with your non-preferred hand. This will be timed by one of the researchers. The night before the study and the day of the study, you will be asked not to moisturize your hands, arms and trunk due to the sensitivity of the motion capture system.

Prior to participating, you will be asked to wear a tight spandex sleeveless white shirt provided to you by the student researcher to eliminate any artificial movements that result from your normal clothes. You will be seated at a table, surrounded by 8 Vicon cameras. To measure performance, 30 special markers will be affixed to your hand, wrist, forearm, elbow, shoulder and trunk with hypoallergenic medical-grade, double-sided adhesive tape, so that our motion analysis system can pick up the fine details of your reaching, grasping and any other movements you will perform. You will then be asked to do a couple of tasks from the Waterloo-Sunnybrook Apraxia Battery such as picking up an object and putting it down in the same location and pantomiming an activity of daily living from the battery.

In addition, you will be asked to provide some background information about yourself, such as age, gender, height and weight. You may also be asked some questions about your health history.

Where will the study take place?

The study will take place in the Ergonomics Laboratory (BMH 1404) at the University of Waterloo, Waterloo, Ontario.

How long will the study take?

The study will take approximately 2 hours to complete.

Can I change my mind about participating?

Participation in this study is voluntary. You are free to withdraw from the study at any time by advising the researcher, and may do so without any penalty.

Are there any risks involved in participating in this study?

Due to the repetitive nature of the reaching and grasping task over trials, you may experience restlessness or loss of attention for the task at hand. As such, optional breaks will be offered every 25-30 minutes during this task. Also, although minimal-to-no risks are anticipated, should you require a break for any reason at any other time, you can simply notify the researcher and the testing can be paused.

Are there any benefits to participating in the study?

There are no direct personal benefits to participating in the study. However, your participation in this research may help quantify dominant and non-dominant limb movements and determine kinematic profiles, which may be applied to individuals suffering from stroke and apraxia. This study will also help us quantify upper extremity motor control during certain activities of daily living. More specifically, it is our objective that the findings from our study be used to direct future research aimed at developing and enhancing tests that can be administered in clinical settings to diagnose and treat apraxia and stroke.

Will any remuneration be provided for my participation in the study?

No remuneration will be provided for participation in this study.

Confidentiality and Security of Data

All information obtained in this study is considered completely confidential. Your name will not be included or in any other way associated, with the data collected in the study. Furthermore, because the interest of this study is in the average responses of the entire group of participants, you will not be identified individually in any way in any written reports of this research. Data collected during this study will be retained indefinitely, in a locked filing cabinet in a locked office in the BMH building, to which only researchers associated with this study have access. Electronic records of your performance will be stored in a similar secure manner without reference to your personal identity. These records will be stored on a computer disk with a unique password that can only be accessed by the researchers involved in the study.

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Consent:

If you agree to participate in this study, please read and sign the attached consent form. Thank you for your interest in our research and for your assistance with this project.

Sincerely,

Tea Lulic, Graduate student

Department of Kinesiology

University of Waterloo

Waterloo, Ontario, N2L 3G1

IN SEARCH OF MANUAL ASYMMETRIES IN AGING DURING PERFORMANCE OF ACTIVITIES OF DAILY LIVING: DOES UPPER LIMB PERFORMANCE BECOME MORE SYMMETRIC WITH AGE?

Consent Form

I, ______________________________________, the undersigned, agree to participate in this study being conducted by Tea Lulic of the Department of Kinesiology at the University of Waterloo under the supervision of Professor Eric Roy and Professor Clark Dickerson. I have made this decision based on the information I have read in the Information Letter and have had the opportunity to receive any additional details I wanted about the study.
I agree to participate in the study with the understanding that:

4. I may withdraw from the study at any time by telling the researcher without penalty
5. I may request that all my data and performance records be withdrawn and destroyed at a later date; and
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I was informed that this project has been reviewed and has received ethics clearance through the Office of Research Ethics (ORE) at the University of Waterloo. I may contact this office if I have any concerns or comments resulting from my involvement in the study by contacting the Director of the ORE (Dr. Maureen Nummelin) at the University of Waterloo (519-888-4567, Ext 36005; maureen.nummelin@uwaterloo.ca)

____

Name of Participant:

______________________________________ ______________

Signature of Participant: Date

____

Name of Investigator/Witness

______________________________________ ______________

Signature of Investigator/Witness Date

APPENDIX B – Participant Demographics

Table I: Healthy Younger Adult Demographics

#	SEX (M/F)	AGE (YRS)
01	F	21
02	F	21
03	F	19
04	M	29
05	M	18
06	F	20
07	F	20
08	M	22
09	F	24
10	F	28
11	M	26
12	F	24
13	M	21
14	M	22
15	M	24
16	F	19
17	M	19
18	M	24
19	M	22
20	F	22
21	F	19
22	M	22
23	F	19
24	F	22
25	F	19
26	F	19
27	M	19
28	F	18
29	F	19
AVG.	---	21.41

Table II: Healthy Older Adult Demographics

#	SEX (M/F)	AGE (YRS)
01	F	83
02	M	72
03	F	67
04	F	85
05	M	80
06	F	66
07	M	81
08	F	66
09	F	69
10	F	65
11	M	82
12	F	84
13	F	72
14	F	67
15	M	79
16	M	75
17	M	71
18	M	74
19	M	76
20	F	76
21	F	67
AVG.	---	74.14

APPENDIX C – The Medical Questionnaire

In Search of Manual Asymmetries in Aging during Performance of Activities of Daily Living: Does Upper Limb Performance Become More Symmetric with Age?

Medical Questionnaire

University of Waterloo

1. What is your dominant hand? ____
2. Have you ever had any neurological problems (ie. strokes, seizures)?

Yes No

If yes, please describe:

____

____

____

3. Have you ever been unconscious for any length of time (ie. head injury)?

Yes No

4. Have you ever had any surgeries?

Yes No

5. Have you ever had a stroke?

Yes No

6. Do you have Parkinson’s disease?

Yes No

7. Do you have a musculoskeletal disease in the upper limb (ie. shoulder pain, osteoarthritis?)

Yes No

APPENDIX D – The Waterloo Handedness Questionnaire

Waterloo Handedness Questionnaire

(Steenhuis, Bryden, Schwartz & Lawson, 1990)

Instructions

Answer each of the following questions as best you can. If you always use on hand to perform the described activity, circle **RA** or **LA** (for right always or left always). If you usually use on hand circle **RU** or **LU** (for right usually or left usually), as appropriate. If you use both hands equally often, circle **EQ.**

Do not simple circle on answer for all questions, but imagine yourself performing each activity in turn, then mark the appropriate answer. If necessary, stop and pantomime the activity

1. Which hand do you use for writing?
   LA LU EQ RU RA
2. In which hand would you hold a heavy object?
   LA LU EQ RU RA
3. With which hand would you unscrew a tight jar lid?
   LA LU EQ RU RA
4. In which hand do you hold your toothbrush?
   LA LU EQ RU RA
5. With which hand would you pick up a penny off a desk?
   LA LU EQ RU RA
6. In which hand would you hold a match to strike it?
   LA LU EQ RU RA
7. With which hand do you throw a baseball?
   LA LU EQ RU RA
8. With which hand would you pet a cat or a dog?
   LA LU EQ RU RA
9. Which hand would you use to ick up a nut or a washer?
   LA LU EQ RU RA
10. Which hand do you consider the strongest?
   LA LU EQ RU RA
11. Over which shoulder would you swing an axe?
   LA LU EQ RU RA
12. With which hand would you pick up a comb?

LA LU EQ RU RA

13. With which hand do you wind a stopwatch?
LA LU EQ RU RA
14. With which hand would you pick up a bat?
LA LU EQ RU RA
15. With which hand would you pick up a piece of paper off a desk?
LA LU EQ RU RA
16. With which hand do you use a pair of tweezers?
LA LU EQ RU RA
17. With which hand would you throw a spear?
LA LU EQ RU RA
18. With which hand would you hold a cloth when dusting furniture?
LA LU EQ RU RA
19. With which hand do you flip a coin?
LA LU EQ RU RA
20. In which hand would you hold a knife to cut bread?
LA LU EQ RU RA
21. With which hand do you use the eraser on the end of a pencil?
LA LU EQ RU RA
22. With which hand would you pick up a toothbrush?
LA LU EQ RU RA
23. With which hand would you hold a needle when sewing?
LA LU EQ RU RA
24. On which shoulder do you rest a baseball bat when batting?
LA LU EQ RU RA
25. In which hand would you carry a briefcase full of books?
LA LU EQ RU RA
26. In which hand would you pick up a jar?
LA LU EQ RU RA
27. With which hand do you hold a comb when combing you hair?
LA LU EQ RU RA
28. With which hand would you pick up a pen?
LA LU EQ RU RA
29. Which hand doe you use to manipulate implements such as tools>
LA LU EQ RU RA
30. Which hand would you use to put a nut washer on a bolt?
LA LU EQ RU RA
31. With which hand would you pick up a baseball?
LA LU EQ RU RA

32. Which hand is the most adept at picking up small objects?.
LA LU EQ RU RA

33. Is there any reason (i.e. injury) why you do not use the hand you prefer to use for any of the above activities?
YES NO (circle one)

If yes, please explain why you do not use your preferred hand and which activities are affected.

34. Hand you ever been given special training or encouragement to use a particular hand for certain activities?
YES NO (circle one)
If yes, please explain the special training and which activities are affected.

APPENDIX E – Kinematic Analyses Summary for Cup ADL

Table III: Statistical analyses for temporal and spatial kinematics in use phase of cup ADL. Analyses which were significant are bolded.

Measure	Main effect hand	Main effect condition	Main Effect Age	Age x Condition	Age x Hand	Hand x Condition
Temporal Measures						
Peak Velocity						
- up (+Y)	**F(1,48) = 10.6, *p* < .01**	**F(1,48) = 27.3, *p* < .01**	**F(1,48) = 24.2, *p* < .01**	F(1,48) = 2.35, *p* = .13	F(1,48) = 1, *p* = .2	F(1,48) = .0, *p* = .9
- down (-Y)	F(1,48) = 1.6, *p* = .2	**F(1,48) = 3.12, *p* < .08**	**F(1,48) = 22.3, *p* <.01**	F(1,48) = .0, *p* = .9	F(1,48) = .8, *p* = .3	F(1,48) = .9, *p* = .3
Cycle Up						
Time to PV	F(1,48) = .8, *p* = .3	F(1,48) = .2, *p* = .6	**F(1,48) = 19.2, *p* <.01**	F(1,48) = .0, *p* = .7	F(1,48) = .0, *p* = .7	**F(1,48) = 4.4, *p* = .03**
Time after PV	F(1,48) = 2.3, *p* = .1	**F(1,48) = 48.2, *p* <.01**	**F(1,48) = 5.8, *p* = .01**	F(1,48) = .0, *p* = .9	F(1,48) = .1, *p* = .7	F(1,48) = .0, *p* = .8
Cycle Duration	F(1,48) = .0, *p* = .8	**F(1,48) = 32.1, *p* < .01**	**F(1,48) = 15.3, *p* <.01**	F(1,48) = .0, *p* = .8	F(1,48) = .0, *p* = .8	F(1, 48) = 2.2, *p* = .1
Cycle Down						
Time to PV	**F(1,48) = 6.5, *p* = .01**	F(1,48) = .1, *p* = .7	**F(1,48) = 14.1, *p* < .01**	F(1,48) = 1.1, *p* = .2	F(1,48) = 1.2, *p* = .2	F(1, 48) = 1.5, *p* = .2
Time after PV	**F(1,48) = 10.9, *p* = .001**	**F(1,48) = 5.6, *p* < .02**	**F(1,48) = 6.9, *p* = .01**	F(1,48) = 0.5, *p* = .4	**F(1,48) = 6.7, *p* = .01**	F(1,48) = 2.6, *p* = .1
Cycle Duration	F(1,48) = .3, *p* = .5	F(1,48) = 2.8, *p* = .1	**F(1,48) = 15.2, *p* < .01**	F(1,48) = 1.3, *p* = .2	F(1,48) = 1.2, *p* = .2	F(1,48) = 2.7, *p* = .1
Joint Angles						
Shoulder Elevation	**F(1,48) = 12.8, *p* < .01**	F(1,48) = 2.3, *p* = .1	F(1,48) = 2.9, *p* = .09	**F(1,48) = 5.9, *p* =.01**	F(1,48) = 1.3, *p* = .2	F(1,48) = .3, *p* = .5
Shoulder Plane	**F(1,48) = 18.6, *p* < .01**	F(1,48) = .1, *p* = .6	**F(1,48) = 10.4, *p* < .01**	F(1,48) = .8, *p* = .3	F(1,48) = .0, *p* = .8	**F(1,48) = 8.8, *p* < .01**
Shoulder Axial Rot.	F(1,48) = 1.7, *p* = .1	F(1,48) = 3, *p* = .08	**F(1,48) = 18.3, *p* = .001**	F(1,48) = .0, *p* = .9	**F(1,48) = 6.4, *p* < .01**	F(1,48) = .7, *p* = .3
Elbow Flexion	F(1,48) = 1.5, *p* = .2	F(1,48) = 2.2, *p* = .1	F(1,48) = 1.6, *p* = .2	F(1,48) = .2, *p* = .6	F(1,48) = 1.4, *p* = .2	F(1,48) = .9, *p* = .3
Forearm Pron/Sup.	**F(1,48) = 4.3, *p* = .04**	**F(1,48) = 10.1, *p* = .02**	F(1,48) = 3.3, *p* = .07	F(1,48) = .1, *p* = .6	**F(1,48) = 5.8, *p* = .01**	F(1,48) = 1.5, *p* = .2
Wrist Flexion	**F(1,48) = 5.9, *p* = .01**	**F(1,48) = 14.9, *p* < .01**	F(1,48) = .01, *p* = .9	F(1,48) = .7, *p* = .3	F(1,48) = .4, *p* = .5	F(1,48) = .5, *p* = .4
Wrist Rad/Ulnar Dev.	**F(1,48) = 11.1, *p* <.01**	F(1,48) = 2.6, *p* = .1	F(1,48) = .9, *p* = .3	F(1,48) = 1, *p* = .3	**F(1,48) = 3.8, *p* = .05**	F(1,48) = 3.1, *p* = .08
Wrist Pronation	F(1,48) = 3.1, *p* = .08	F(1,48) = 1.4, *p* = .2	F(1,48) = 2.6, *p* = .1	F(1,48) = .7, *p* = .3	F(1,48) = .2, *p* = .6	F(1,48) = .1, *p* = .6

APPENDIX F – Kinematic Analyses Summary for Knife ADL

Table IV: Statistical analyses for temporal and spatial kinematics in use phase of knife ADL. These analyses included 12 older adults and 20 younger adults, and were performed only on participants whose primary axis of movement was in X direction (forward/backward). Analyses which were significant are bolded.

Measure	Main effect hand	Main effect condition	Main Effect Age	Age*Condition	Age*Hand	Hand*Condition
Temporal Measures						
Peak Velocity						
- away (+X)	F(1,30) = .8, *p* = .3	F(1,30) = .6, *p* = .4	F(1,30) = .8, *p* = .3	F(1,30) = 3.1, *p* = .08	F(1,30) = 1.4, *p* = .2	F(1,30) = 3.2, *p* = .08
- towards (-X)	F(1,30) = 3.2, *p* = .08	F(1,30) = .8, *p* = .3	F(1,30) = 1.5, *p* = .2	F(1,30) = 2.7, *p* = .1	F(1,30) = 2.7, *p* = .1	**F(1,30) = 7.6, *p* < .01**
Cycle						
Time to PV	**F(1,30) = 6.9, *p* = .01**	F(1,30) = .4, *p* = .5	**F(1,30) = 6.5, *p* = .01**	F(1,30) = .4, *p* = .5	F(1,30) = 3.8, *p* = .06	F(1,30) = .0, p = .3
Time after PV	F(1,30) = 1.4, *p* = .2	F(1,30) = .2, *p* = .6	**F(1,30) = 10, *p* = .003**	F(1,30) = 1.4, *p* = .2	F(1,30) = .1, *p* = .7	F(1,30) = 1.5, *p* = .2
Cycle Duration	**F(1,30) = 6.3, *p* = .01**	F(1,30) = .3, *p* = .5	**F(1,30) = 8.9, *p* = .005**	F(1,30) = 1, *p* = .3	F(1,30) = 2, *p* = .1	F(1,30) = 2.3, *p* = .1
Joint Angles						
Shoulder Elevation	**F(1,30) = 37.1, *p* < .0001**	**F(1,30) = 14.8, *p* < .01**	F(1,30) = .0, *p* = .9	F(1,30) = .0, *p* = .9	**F(1,30) = 6, *p* < .01**	**F(1,30) = 10, *p* < .01**
Shoulder Plane	**F(1,30) = 30.7, *p* < .0001**	F(1,30) = .4, *p* = .5	F(1,30) = 1.1, *p* = .2	F(1,30) = 1.1, *p* = .2	F(1,30) = .7, *p* = .3	F(1,30) = 3, *p* = .08
Shoulder Axial Rot.	F(1,30) = .3, *p* = .5	F(1,30) = 4.1, *p* = .05	**F(1,30) = 4.6, *p* = .03**	**F(1,30) = 6.6, *p* = .01**	F(1,30) = .1, *p* = .6	F(1,30) = 2.3, *p* = .1
Elbow Flexion	F(1,30) = 1.7, *p* = .1	F(1,30) = .0, *p* = .7	F(1,30) = 1.1, *p* = .2	F(1,30) = 2.3, *p* = .1	F(1,30) = .1, *p* = .7	F(1,30) = .7, *p* = .3
Forearm Pron/Sup.	F(1,30) = 3.5, *p* = .06	**F(1,30) = 14.6, *p* < .01**	F(1,30) = .1, *p* = .7	F(1,30) = 4, *p* = .05	F(1,30) = .3, *p* = .5	F(1,30) = 3.5, *p* = .06
Wrist Flexion	F(1,30) = 2.4, *p* = .1	**F(1,30) = 17.8, *p* < .01**	F(1,30) = .2, *p* = .6	**F(1,30) = 15.1, *p* < .01**	F(1,30) = 3.8, *p* = .05	F(1,30) = .9, *p* = .3
Wrist Rad/Ulnar Dev.	F(1,30) = .1, *p* = .7	**F(1,30) = 18.6, *p* < .01**	F(1,30) = 2.1, *p* = .1	**F(1,30) = 5, *p* = .03**	F(1,30) = .0, *p* = .8	F(1,30) = .1, *p* = .7
Wrist Pronation	F(1,30) = .2, *p* = .6	**F(1,30) = 12.6, *p* < .01**	F(1,30) = .1, *p* = .7	**F(1,30) = 7.3, *p* = .01**	**F(1,30) = 4.2, *p* = .04**	F(1,30) = .3, *p* = .5