A BIOMECHANICAL ANALYSIS OF BEHAVIOR IN THE KITCHEN FOLLOWING AN ACUTE UPPER EXTREMITY INJURY

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by

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ABSTRACT

A brace that simulates a short arm cast was applied to fifteen participants who were administered a battery of standardized manual dexterity tests. These same participants were then asked to perform simulated kitchen tasks (pouring from a pitcher and lid removal from a container). Timed performance and postures were evaluated across both sets of tasks, with and without the brace.

Results showed that there was a significant overall effect of the intervention, an increase in time needed to complete the standardized dexterity tests ($p < 0.05$). For the kitchen tasks, removing the lid from a container was also significantly slower $W(15)=3$, $p < 0.05$. Pouring water from the pitcher was also significantly slower depending on the initial positioning of the pitcher at $\alpha = 0.05$ for two of the three conditions. There were also some significant changes in the way people moved their bodies to complete tasks after the intervention.

BIOGRAPHICAL SKETCH

Laura Anderson graduated from Cornell University in 2013 with a Bachelors of Science in Design and Environmental Analysis concentrating in Interior Design. Her interest in the research for this masters thesis stemmed from personal experience with acute injuries and a desire to improve the environments in which people work and live.

DEDICATION

I would like to dedicate this work to all my broken bones, without which, my curiosity for the field of ergonomics and biomechanics and this study, would have never happened.

ACKNOWLEDGMENTS

First and foremost I would like to thank my advisor and thesis chair Dave Feathers for his continuous support in my explorations and pursuits in the field of Human Factors and Ergonomics. Furthermore, I would like to thank Elaine Wethington for her flexibility and her invaluable insight into the world of Aging in Place as my minor chair. I would also like to thank Rhonda Gilmore for always making sure I was never afraid to chase my academic and professional dreams no matter how lofty.

This thesis would not have been accomplished without funding by the Department of Design and Environmental Analysis. This research in no way expresses the opinions or beliefs of Cornell University, the College of Human Ecology or the Department of Design and Environmental Analysis.

A special thank you to my family and friends for helping me triumph over a fifth year on the hill. You are all an inspiration.

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LIST OF ABBREVIATIONS

AAOS - American Academy of Orthopedic Surgeons

ADL - Activity / Activities of Daily Living

INJ - Injury / Injured

MDTs - Manual Dexterity Test(s)

MMDT - Minnesota Manual Dexterity Test

NSC - National Safety Council

PI - Principle Investigator

PP - Purdue Pegboard test

R-R-L - Participants using their Right hand for position 1, Right hand for position 2 and Left hand for position 3.

R-R-R - Participants using their Right hand for position 1, Right hand for position 2 and Right hand for position 3.

PREFACE

At any given time, our patterned interactions and behaviors with our home environment may be altered, potentially leading to a number of secondary health issues. Whether impaired movement is the direct result of an acute injury or an immobilization device in place to heal an injury, our inability to interact with our environment using our normal methods may have serious implications. It is estimated that over 53% of men and 67% of women are affected by or have been diagnosed with an upper limb disorder or injury (Walker-Bone et al., 2004). This change in mobility has a large impact on a number of daily life activities and rituals, especially in the kitchen.

Immobilization of different areas of the upper extremity leads to compensatory movements to allow people to move in a way that will help them to complete a task. A list of these movements can be summarized in Table 1. I was able to observe this through the use of standardized dexterity tasks and a simulated kitchen environment. Lastly, I wanted to observe signifiers in the environment to determine if environmental cues had an impact on how participants would change or adjust their behavior in light of their injury.

The particular simulated injury that was chosen for this study reflects that of a forearm fracture, an injury common to both children and older adults. These findings may establish new design guidelines for a kitchen that will not only give users with upper extremity immobility an opportunity to work more fluidly in the kitchen, but will also give users with full range of motion an opportunity to have a kitchen that will support them across their life span.

Stabilization of:	**Compensatory Movements:**
WRIST	
Affected movements:	
Flexion / Extension	Internal and external rotation with flexion and extension at the elbow
Radial / Ulnar Deviation	Internal and external rotation at the shoulder
Stabilization of:	**Compensatory Movements:**
FOREARM	
Affected movements:	
Pronation	Wrist flexion, ulnar deviation, abduction and internal rotation of the shoulder, possible contralateral trunk lateral trunk flexion
Supination	Wrist extension, radial deviation, adduction and external rotation of the shoulder and possible ipsilateral trunk lateral flexion
Stabilization of:	**Compensatory Movements:**
ELBOW	
Affected movements:	
Flexion	Abduction at the shoulder, flexion and extension at the shoulder
Extension	Adduction at the shoulder
Stabilization of:	**Compensatory Movements:**
SHOULDER	
Affected movements:	
Flexion	Elbow flexion, with sagittal trunk flexion
Abduction	Elbow extension with lateral trunk flexion
Adduction	Wrist flexion with additional elbow flexion
Internal / External Rotation	Pronation / supination of the forearm

Table 1 - Matrix of Movements

BACKGROUND

The Kitchen as a Hazardous Environment for Able Bodied Users

Nearly 40% of all domestic accidental deaths and 24% of domestic accidents occur in the kitchen (Ward 1974). In 1972 the Institute for Consumer Ergonomics conducted a survey to examine the thermal and acoustic levels of 262 homes built to current British standards. Ward argues that ergonomic factors are critical to consider in kitchen design due to the rise of appliances and equipment in the kitchen and the decline of space for tasks. The appliances are taking up more space and are changing the ways in which users are interacting within the kitchen. If ergonomic criteria are not taken into consideration when designing kitchens for this new age of appliances, there may be serious consequences. While kitchens have likely improved in the past 40 years, the kitchen still remains one of the most dangerous rooms in the home, along with the bathroom (CDC, 2008).

Guilford (1973) studied the predictions of accidents in the standardized home environment using a kitchen model in a laboratory setting. The subjects, 262 women, were asked to perform a set of tasks, requiring about two hours of time. Each participant was tested twice at different times of day and was observed the entire time. 'Scores' were given to each subject based on the number of personal injury accidents, property damage accidents, total kitchen accidents (sum of the property and personal accidents) and near accidents in the test kitchen. Near accidents were considered events that in an uncontrolled environment could had resulted in an accident such as spilled liquids and dropped debris.

The findings indicated that the total number of kitchen accidents was 714. Approximately 52% of these accidents involved personal injury and property damage accounted for the remaining 48% of accidents. A total of 648 near accident incidents were also recorded. This data lead to the finding of six categories of behavior that can be correlated with kitchen accidents: Preparation, Makes use of correct tools, Unsanitary practices, Unsafe practices, Safe practices, Fails to follow directions. To strengthen these findings, Guilford compared accident incidence in automobiles (of the subjects that were licensed) to show a positive relationship to accident occurrence in other settings.

According to the National Safety Council (NSC), every 16 minutes a fatal injury occurs in the home, and every 4 seconds a disabling injury occurs. In 2002 alone there were 33,300 fatalities and 8,000,000 disabling injuries that occurred at home (NSC, YEAR).

Knowing more about the way users interact in this altered condition could lead to potential design interventions. This information may also change the way physical therapists and doctors interact with patients following an acute upper extremity injury regarding their advice on patient home care.

"Healthy" Populations

While a notable number of studies have been conducted on the elderly and permanently disabled, comparatively fewer studies have examined acute conditions impacting a short period of time (6-8 weeks) which is generally not enough time not for users to develop alternative strategies for activities of daily living. Additionally, this time frame may prove to not make it economically sensible to purchase any assistive technology. In a study conducted in 1998 by Mathers and Weiss there were 1,465,874 estimated cases of hand/forearm fractures, accounting for 1.5% of all emergency department cases. Radius and/or ulna fractures comprised the largest proportion of fractures (44%). Of all the possible places a person could become injured it is important to call attention to the fact that 30% of these incidents occurred within the home (Chung, 2001). Seeing as accidental falls caused 47% of the fractures, it would not be alarming to presume that older adults made up the majority of this injured population. However, that would be a false assumption. The majority of people that suffered from fractures as a result of an accidental fall were actually ages 5 - 14, with age groups 15-24 and 25-34 following closely in second (Chung, 2001).

Forty-nine million individuals over the age of fifteen in America suffer from a disability (Brault, 2009). The percentage of the population with some disability is expected to increase in the near future, particularly as a result of the aging baby boomer generation (Sangelkar 2011). While a disability is frequently thought of as a permanent or potentially congenital problem, "disablement" refers to impacts that chronic and acute conditions have on the functioning of specific body systems and on people's abilities to act in necessary, usual, expected and personally desired ways in their society (Verbrugge 1994). These necessary, usual and expected functions are referred to as "activities of daily living" and include many aspects of our daily lives from getting dressed to preparing a meal.

Forearm Fractures

Fractures and injuries of the forearm are common and occur in both adults and adolescents. While pediatric healing methods generally only involve casting, adult fractures may require more extreme measures such as surgery that will also ultimately end in casting the forearm (Arnander and Newman 2006). A longitudinal study by Goulding, et al., (2000) examined children that have suffered distal forearm fractures and have found that they may be a factor in fractures later in life. Additionally, forearm fractures and hip fractures are known manifestations of osteoporosis (Cuddihy, et al. 1999) making women especially susceptible. The study by Cuddihy followed women ages 35 plus over a 20 year period and were able to find convincing evidence that the "occurrence of a distal forearm fracture is a strong predictor of future fracture risk." The alarming prevalence of forearm fractures across the lifespan makes studying the subsequent period following an injury so crucial.

Activities of Daily Living and Injury

Our daily lives largely consist of activities that we know as routine. From childhood on, we learn these habits and skills and do not think about them until illness, injury, or aging makes them difficult or impossible to do (Kroemer, 2006). While we are fortunate enough to have a relatively healthy aging population, about 30% of persons older than 65 years old in the United States have limited capacities for self-care and home-management activities (D. B. D. Smith, 1990).

Of this older population (age 65 and older), 35% report falling at home, at least once, within a year (Blake, et al., 1988). Injuries most prevalent following a fall, regardless of age were knee contusions and hip fractures (Mathers and Weiss, 1998). While a hip fracture may be regarded as a more "serious" injury, wrist fractures may be as disabling as vertebral or hip fractures with respect to some specific activities of daily living such as meal preparation (Edwards, 2010). Even more alarmingly, the incidence rate for limb fractures among women is double that of the incidents reported for men (Ismail et al. 2002).

Hand Dominance

It may not be until an injury occurs that a user realizes how much they rely on their dominant hand (Kawabata, 2013). Not only do users generally have a preference for using one hand over the other, users have been found to be stronger in the dominant hand (Kawabata, 2013), allowing them to complete a greater range of tasks. Handedness is not only a physical feature; studies have shown ties to lateralized brain development (Chapman, 1987). Based on the neurological and physical aspects of handedness, it is difficult to quickly train the body to use the non dominant hand for everyday activities.

Additionally, design issues may arise when using the non dominant hand, (especially when a user is right hand dominant) as many tools have been designed for right hand use. While left handed users may experience this more often, left-handers, as well as right- handers, consistently perform worse with the non-dominant hand as compared to the dominant one in a variety of behavioral tasks (Garonzik, 1989).

Standardized Dexterity Tests

While observing adults in the home environment with an upper extremity injury would provide insight into the behaviors that arise as the result of an injury, it is impossible to create ergonomic recommendations for the proper design of tasks and equipment from an activity of daily living alone and elemental components of the tasks must be considered (Kroemer, 2006). Combining tasks required of daily living with a selection of dexterity tests will best help us to observe or assess any changes that may be present when people are with or without an injury. The tests selected for this experiment (Minnesota Manual Dexterity and Purdue Pegboard) have been selected based on their reliable performance measures assessing hand function and manual dexterity in previous studies.

HYPOTHESES

This study investigated the ways in which people overcome the obstacles faced during temporary upper extremity immobility. My primary hypothesis was that the time needed to complete both the standardized dexterity tests as well as the simulated kitchen tasks would increase following the implementation of the forearm brace.

Secondly, I hypothesized that participants would need to change their regular behaviors after losing the ability to pronate and supinate (turning of the wrist as a result of an immobility device or injury). Specifically, it was postulated that participants would be less likely to use their non dominant, uninjured hand and that they would attempt to use their stabilized dominant hand, resulting in awkward and potentially even dangerous postures.

With this in mind, I also sought out to test the impact of environmental cues on users' decision making behaviors. By making tasks more convenient to be completed with their non dominant hand, it was thought that participants would unconsciously perform the task as the cue suggested. The kitchen was of particular interest, due to the many activities of daily living that occur in this environment.

METHODS

Participants

The participants for this study were fifteen, female university students ranging from ages 18 to 25. The sample was recruited using SONA, a social science recruiting system. All participants were right hand dominant and have never suffered an acute musculoskeletal injury to either upper extremity and additionally reported never having any neurological or vascular conditions impacting the upper extremity. Controlling for right hand dominance and no previous musculoskeletal injuries ensured that there were no learned behaviors from a previous injury or physical therapy or any thoughts about alternative ways of completing activities of daily living. At the start of the experiment, all participants were in physically healthy shape (self reported). A participation information chart was used to collect anthropometric and performance data which can be seen in Figure 1.

Procedure

The following standardized dexterity tests were used to determine participants' baseline dexterity capabilities: Lafayette Instrument Purdue Pegboard (PP) test, Model 32020 (right handed and left handed), the turning portion of the Lafayette Instrument Minnesota Manual Dexterity Test (MMDT), Model 32023, and the placing portion of the Lafayette Instrument Minnesota Manual Dexterity Test, Model 32023. A convenience sample of two students were recruited to review the proper protocol and administration of the standardized dexterity tests as well as the simulated kitchen tasks. Video footage of the participants was taken from the shoulder down for later analysis. The standardized dexterity tests were administered in random sequence to combat order effects, but for the purpose of clarification, the standardized dexterity tests will be presented in this methods section as if the participants has completed the PP, followed by the MMDT (turning and placing), in that order.

Participants were asked to sit at a workstation equipped with a table and chair of standard height, 30 inches and 19 inches, respectively. Before the start of the test, participants were given the chance to practice placing pins onto the pegboard. Each participant was administered the right handed, left handed PP tests according to the standard procedures, as directed by the manufacturers of the test, Lafayette Instrument. Twenty-five pins were placed in the left hand and right hand cups for a total of fifty pins. Participants were asked to place as many pegs into the corresponding holes as they could in thirty seconds. The right hand was tested first, followed by the left. A trial for both hands was run three times. Scores were immediately recorded on the participant information chart. The average score (number of pins) for the three trials was the score used for analysis.

		ANTHROPOMETRIC DATA				
Participant Number	*Pinch Strength*	RIGHT HAND		LEFT HAND		
	1	**2**	**3**	***1****	***2****	***3****
NETID						
	Grip Strength	RIGHT HAND		LEFT HAND		
	1	**2**	**3**	***1****	***2****	***3****
	Pinch Strength	RIGHT HAND WITH CAST		*Grip Strength*	RIGHT HAND WITH CAST	
	1	**2**	**3**	***1***	**2**	**3**
Acromium to Lateral Epicondyle		*Radiali to Radial Styloid*		*Radial Styloid to Fingertip 3*		*Cum.Length*
		PURDUE PEGBOARD PRE INTERVENTION				
	TRIAL 1 (R)	**TRIAL 2 (R)**	**TRIAL 3 (R)**	**TRIAL 1 (L)**	**TRIAL 2 (L)**	**TRIAL 3 (L)**
# OF PINS						
SCORE						
%TILE						
		MMDT PRE INTERVENTION				
	PLACING TEST 1	**TURNING TEST 1**	**PLACING TEST 2**	**TURNING TEST 2**		
TIME						
SCORE						
		PURDUE PEGBOARD - POST INTERVENTION				
	TRIAL 1 (R)	**TRIAL 2 (R)**	**TRIAL 3 (R)**	**TRIAL 1 (L)**	**TRIAL 2 (L)**	**TRIAL 3 (L)**
# OF PINS						
SCORE						
%TILE						
		MMDT POST INTERVENTION				
	PLACING TEST 1	**TURNING TEST 1**	**PLACING TEST 2**	**TURNING TEST 2**		
TIME						
SCORE						
	PLACING TEST 1*	**TURNING TEST 1***	**PLACING TEST 2***	**TURNING TEST 2***		
TIME						
SCORE						

Figure 1 - Participant Information Chart

Remaining at the workstation, the participant was able to rest, without touching the work surface while the next standardized test was arranged. Participants were shown an example on how to complete the MMDT two hand turning test. The two hand turning test required participants to pick up a disk, turn it over , change the disk to the other hand and replace it in the frame. The leading hand (the hand that initially picks up the disk) alternates in each row, as can be illustrated in Figure 2. The MMDT two hand turning test was then administered.

Figure 2 - Starting Direction and Sequence for the MMDT Turning Test

Participants rested while the MMDT placing test was positioned. The participants were shown a demonstration on how to complete the MMDT placing test. The demonstration was reset and the participants were asked to complete the MMDT placing test. These trials were repeated two more times each as described in the standard procedures as directed by the manufacturers of the test, Lafayette Instrument. Scores were immediately recorded on the participant information chart after each variation of the MMDT. Scores reflected the number of seconds it took participants to complete the tests. Both the turning test and placing test were administered twice each, for a total of four MMDT trials. The average of the two placing test scores and the average of the two turning tests scores were used for analysis.

Participants were then asked to move to the second workstation. This work station consisted of work surface that was 36" tall to simulate an industry standard kitchen counter. Two tasks were to be completed on the work station. Task one consisted of asking participants to demonstrate how they would approach and pour something from the pitcher into a cup, both provided on the work surface. Task two required participants to remove the lid from a plastic food storage container.

For the pitcher task, participants were asked to stand in front of the workstation. When they were properly in position they were asked to cover their eyes. During that time, the Principle Investigator (PI) arranged the pitcher and cup into one of the three possible positions as shown in Figure 3. The PI then counted down from three, and on the word go, participants opened their eyes, intuitively grabbed the pitcher and the cup, completed the simulated pouring task and returned their hands to their sides. Participants returning their hands to their sides signaled to the PI that the task had been completed and that the timer should be stopped.

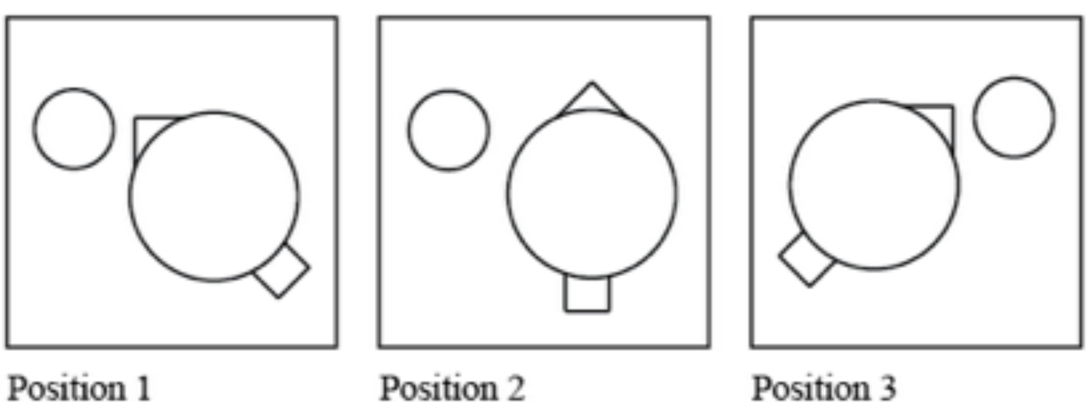

Figure 3 - Pitcher Positions

The logic for placing the pitcher in three different positions as noted was to observe the ways in which participants would naturally approach the task. Participants were told to intuitively reach for the cup and pitcher. Participant times were recorded after each trial, along with notation for which hands the participant used.

Participants were then asked to move to the scanning area. Scans were taken in the initial grasping position (Position Starting) and in the active pouring position (Position Pouring). Figure 4 more clearly illustrates these positions. Scans were taken using a Human Solutions ASSYST AVM Body Scanner. The scanner is a light-based, eye safe scanner that allows for exact three-dimensional images of the participants to observe postures of the upper extremity.

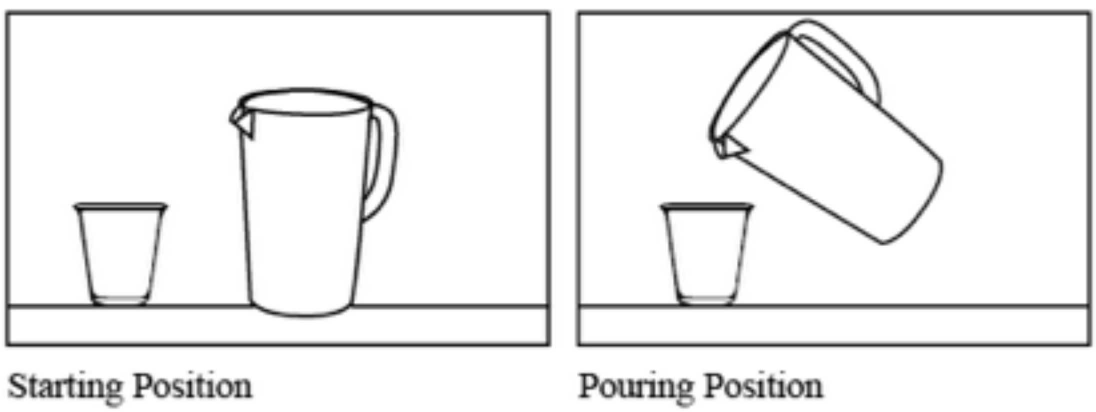

Figure 4 - Pouring Task Positions

The scans taken were contingent on the Participant's reaching, grasping and pouring behavior during the timed task. Since none of the participants used their left hand for position 2, participants were classified as R-R-L (right hand for positions 1 and 2, left hand for position 3) or R-R-R (right hand used for all positions). Figure 5 more clearly illustrates the behaviors of the R-R-L and R-R-R participants.

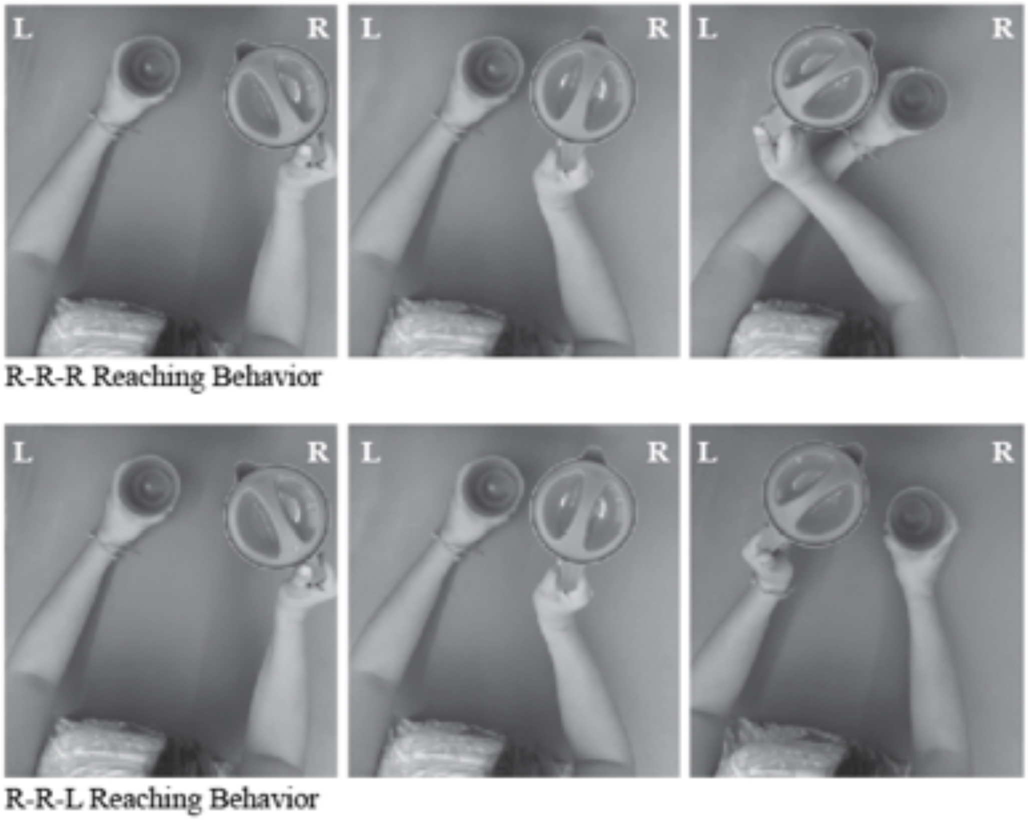

Figure 5 - Reaching Behaviors for Participants Classified as R-R-L or R-R-R

R-R-L participants had scans taken in Position 1, pausing at Starting Position and Pouring Position (Figure 4) with their right hand holding the pitcher, left hand on the cup and then with their left hand on the pitcher, right hand on the cup (again, pausing at the Starting and Pouring positions). R-R-R participants were scanned in Position 1 (Starting and Pouring) with their right hand holding the pitcher, left hand on the cup and then in Position 3 (Starting Position) with their right hand holding the pitcher, left hand on the cup to capture the awkward postures exhibited during the timed task.

Participants were then asked to complete task two, removing the lid from a plastic food storage container. Placement of the container was standardized as well to control for reaching distance. Participants were then asked to complete the container lid removal task. Participants began with their hands at their sides. The PI counted down from 3 and said the word 'go' to indicate that the timer had started and that participants should complete the task. Participants then removed the lid from the container, placed the lid beside the container and placed their hands back at their sides. The task was complete and the timer was stopped when participants returned their hands to their sides.

Participants were then asked to move to the scanning area, where scans were taken in Position Closed and Position Open (partial removal of the lid) as they did during the timed task. Figure 6 demonstrates how the majority of the participants approached the task.

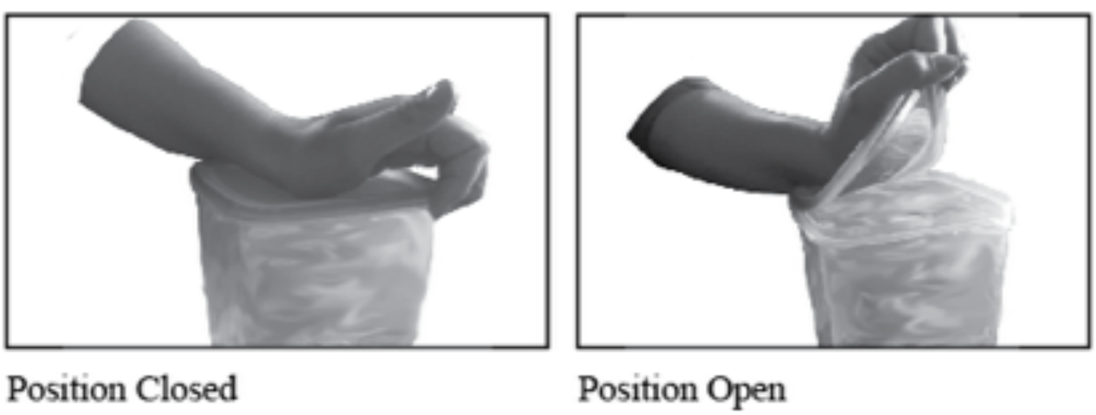

Figure 6 - Container Lid Removal Task Positions

After a five minute break, participants were asked to complete the remainder of the study. Participants were asked to return to the standardized manual dexterity test workstation and remain seated. A Medline Industries, Inc. Universal Wrist and Forearm Splint for the Right Hand was placed on the right forearm of the participant to simulate the casting procedures for many common forearm and wrist injuries (American Association of Orthopedic Surgeons, 2011). Additional stabilization was added to the cast to ensure that the conditions properly simulated an injured forearm in a hard cast. Participants were then run through the same battery of standardized dexterity tests, in a new order, following the same procedures as previously stated for each test. Upon completion of the standardized dexterity tests, the participant was again asked to complete the pouring and container lid removal task at the timing station and the same scans as previously described were taken based on participant behaviors. Participants were again asked to naturally approach the tasks and were then scanned at the same positions in space previously recorded.

Measurements

Measurements between landmarks were taken before the start of the standardized dexterity tasks (acromion to lateral epicondyle, radiale to radial styloid, radial styloid to fingertip 3 and overall arm length). These bony landmarks were also used in video observation to standardize the measurements of awkward postures as defined by the abduction and rotation of the shoulder post intervention (implementation of the splint) to compensate for the loss of pronation and supination at the forearm. The angle at the humeroradial joint and the angle of humeral abduction and flexion were recorded. Internal and external rotation of the shoulder was also recorded.

Measures of dexterity and strength were also recorded before the start of the experiment. A Baseline Hand Dynamometer was used to record grip strength in the right and left hand of every participant. Tip to tip pinch strength was also recorded using a Baseline Pinch Gauge and was recorded for both the dominant and non dominant hands. These measurements were retaken on the dominant arm after the administration of the arm splint.

Each standardized dexterity tasks has a corresponding scoring system. Scores and times for each dexterity test were recorded manually after each participant task on the Participant Information Chart (Figure 1). Scores for MMDT were the time needed to complete the task and scores for the PP were the number of pegs participants were able to place in 30 seconds with each hand. As previously mentioned, the averages for each respective test and trial were used for analysis. Scores and times were compared and analyzed pre and post immobilization intervention to determine whether the immobilization device had an effect on the performance and time requirements of the dexterity tasks.

Video footage taken while participants were performing standardized dexterity tests was examined to determine if there were increased rates of internal and external rotation of the shoulder and shoulder abduction as a result of placing the forearm splint on the participants. The video footage also helped to ensure that the correct scores, times and number of errors were recorded at the time of the study.

For the pouring and container lid tasks, participants' arm postures were scanned in the previously mentioned positions. For the 3D scans, a quasi static biomechanical approach was used to measure the captured anthropometric data.

Awkward postures were determined by previous biomechanical postural studies. The different configurations for the pitcher task were to observe if environmental cues had any impact on how participants approached the task following the implementation of the forearm splint.

Data Analysis

Due to the inherent differences between the standardized dexterity tests (scores on the MMDT are represented by time while scores on the PP are represented by the number of pegs placed in thirty seconds) scores from the MDT tasks were standardized. A Wilcoxon signed ranks test was administered to determine if there were significant differences in performance following the placement of the forearm splint. Wilcoxon signed ranks was also used to determine if there were significant differences in time performance for the pouring and container tasks.

The data captured from the 3D scans was used to record measurements between bony landmarks (joint angle measurements) to observe incidences of awkward postures. A paired t-test was conducted to determine if there were significant changes in ab/adduction, internal/external rotation and flexion of the shoulder as well as flexion or extension in the elbow following the placement of the forearm splint.

RESULTS

Standardized Dexterity Tests

Figure 7 provides summary data showing mean performance on the MMDT Turning and Placing tests before and after the placement of the Medline Universal Wrist and Forearm Splint. Time needed to complete the MMDT Placing test increased by 15.22% while time required to complete the MMDT Turning test increased by 8.61%.

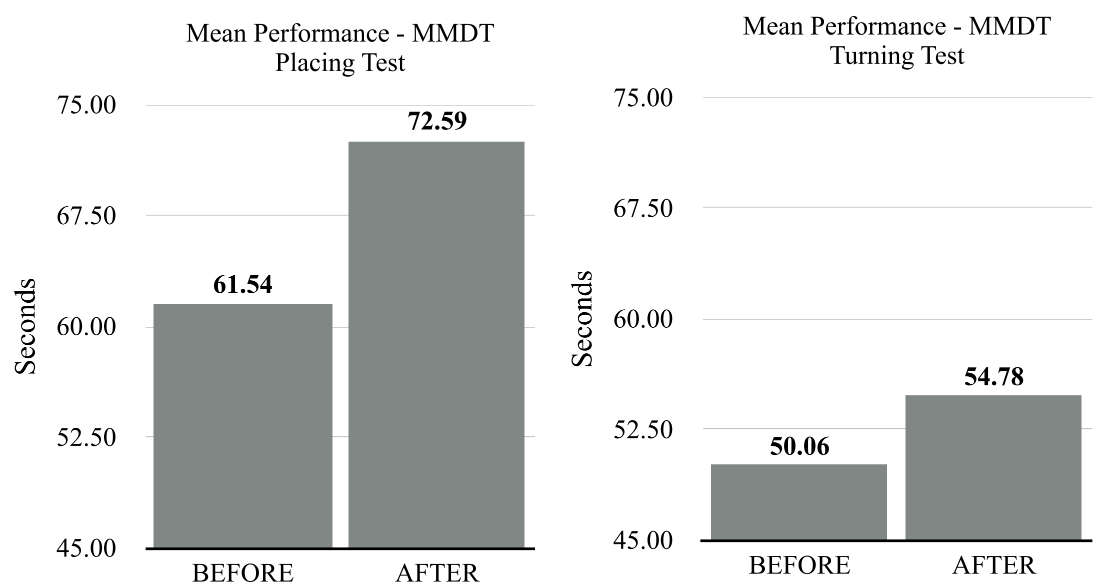

Figure 7 - Summary of Mean Performance on the MMDT

In the PP right and left handed tests, the number of pegs placed with the right hand decreased by 19.71% following the placement of the splint while the number of pegs placed with the left hand increased by 4.07% for the second round of PP tests. The summary data for mean performance on the PP test for the right and left hands can be found in Figure 8.

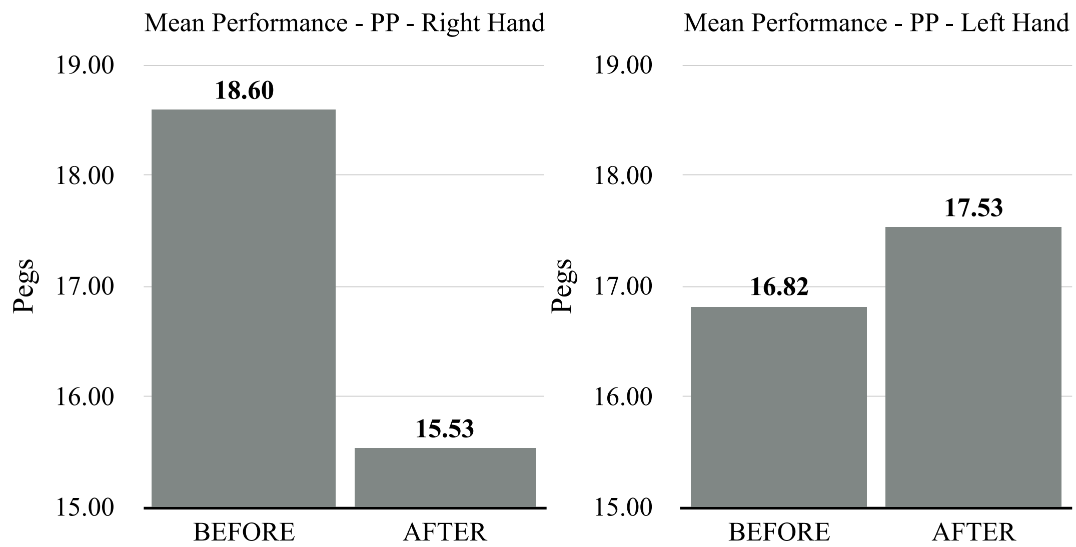

Figure 8 - Summary of Mean Performance on the PP

A Wilcoxon T Test was conducted and showed a significant difference in performance at $\alpha = 0.05$ with and without the splint for both MMDT and the PP conducted on the right hand. No significant difference in performance was found for the left hand PP test. A summary of the analyses from the Wilcoxon T Tests conducted across the MDTs can be found in Table 5.

Test	Results
MMDT Placing Test	W(15)=0, $p < 0.05$
MMDT Turning Test	W(15)=8, $p < 0.05$
PP Right Hand	W(15)=0, $p < 0.05$
PP Left Hand	W(15)=33, $p > 0.05$

Table 5 - Summary of Wilcoxon T Statistical Analyses for MDTs

Kitchen Tasks

Time data recorded from the kitchen tasks showed a significant increase in time needed to remove the lid from the container following the placement of the forearm splint W(15)=3, $p < 0.05$. There was no significant increase in time for the pouring task when the pitcher originated in position 1. A significant difference in time could be seen when the pitcher was placed in positions 2 and 3. A summary of the results from the timed kitchen tasks can be found in Table 6.

Task	**Results**
Container Lid Removal	W(15)=3, $p < 0.05$
Pouring from Position 1	W(15)=36, $p > 0.05$
Pouring from Position 2	W(15)=21.5, $p < 0.05$
Pouring from Position 3	W(15)=9, $p < 0.05$

Table 6 - Summary of Wilcoxon T Statistical Analyses for Kitchen Tasks

The measurements taken from the scan were analyzed with a paired t-test to determine if there was a significant change in posture. A summary of these results organized by joint and movement type can be found for the container task in Table 7 and for the Pouring task in Table 8.

Condition	Joint	Movement	t	df	Results	95% CI
Container - Closed	Shoulder	AD/ABduction	-1.60	14	P = 0.132	(-14.99, 2.19)
	Shoulder	Flexion/Extension	-2.12	14	P = 0.052*	(-16.61, 0.08)
	Shoulder	Internal/External Rotation	-1.21	14	P = 0.246	(-17.37, 4.84)
	Elbow	Flexion/Extension	-0.62	14	P = 0.548	(-15.23, 8.43)
Container - Open	Shoulder	AD/ABduction	-2.88	14	P = 0.012*	(-23.27, -3.40)
	Shoulder	Flexion/Extension	-3.49	14	P = 0.004*	(-24.64, -5.89)
	Shoulder	Internal/External Rotation	-1.64	14	P = 0.123	(-13.08, 1.74)
	Elbow	Flexion/Extension	-1.52	14	P = 0.150	(-21.50, 3.63)

Table 7 - Paired T-test results comparing ROM before and after placement of the splint on the Container Task

*Notes: α: 0.05 is the level of significance, * indicates significant results*

Condition	Joint	Movement	t	df	Results	95% CI
Pitcher - Starting - 001	Shoulder	AD/ABduction	-2.52	14	P = 0.026*	(-14.08, -1.07)
	Shoulder	Flexion/Extension	-2.39	14	P = 0.033*	(-13.88, -0.69)
	Shoulder	Internal/External Rotation	-2.45	14	P = 0.032*	(-26.87, -1.46)
	Elbow	Flexion/Extension	-5.32	14	P = 0.000*	(-20.28, -8.49)
Pitcher - Starting - 003	Shoulder	AD/ABduction	-1.22	14	P = 0.244	(-15.11, 4.17)
	Shoulder	Flexion/Extension	0.55	14	P = 0.592	(-7.17, 12.11)
	Shoulder	Internal/External Rotation	-1.85	14	P = 0.086	(-17.29, 1.29)
	Elbow	Flexion/Extension	-0.04	14	P = 0.971	(-11.95, 11.55)
Pitcher - Pouring - Right	Shoulder	AD/ABduction	-3.03	14	P = 0.009*	(-36.49, -6.25)
	Shoulder	Flexion/Extension	-2.88	14	P = 0.012*	(-33.71, -4.96)
	Shoulder	Internal/External Rotation	-0.62	14	P = 0.548	(-19.15, 10.69)
	Elbow	Flexion/Extension	-1.74	14	P = 0.105	(-23.99, 2.56)

Table 8 - Paired T-test results comparing ROM before and after placement of the splint on the Pitcher Task

*Notes: α: 0.05 is the level of significance, * indicates significant results*

DISCUSSION

Standardized Dexterity Tests

A Wilcoxon T Test showed significant decreased performance after the placement of the splint at $\alpha = 0.05$ which was measured by increased time needed to complete the task in the case of the MMDT and by fewer number of pegs placed in PP test. Though the number of pegs placed with the left hand was more for the second administration of the test, there was no significant change in the number of pegs placed with the left hand, showing no increase or decrease in performance due to learning effects or fatigue respectively.

Both the PP and MMDT had verbal scales to represent performance. Both had five categories for verbal performance: Very Low, Low, Average, High, Very High (MMDT) and Poor, Low Average, Average, High Average and Excellent (PP). For the sake of comparison, since both groups had five divisions of verbal performance, the verbal categories for the PP were referred to as follows: Poor = Very Low, Low Average = Low, Average = Average, High Average = High and lastly Excellent = Very High. These verbal categories for performance were used to determine "high" and "low" performers as discussed in the case study.

Kitchen Tasks

The initial position of the pitcher appeared to have an impact on the time it took participants to complete the tasks. The only scenario in which there was no significant increase in time to complete the pouring task was when the pitcher was in position 1, very clearly oriented towards the right side of the body.

Starting position for the pitcher also had an effect on which hand participants used to reach for the pitcher to complete the pouring task. 100% of the time, participants reached for the pitcher with their dominant hand when the pitcher was in Position 1. 100% of participants reached for the pitcher with their dominant hand when the pitcher started in position 2 and lastly about 66.67% of participants reached with their dominant hand when the pitcher was initially placed in position 3. A summary table of the reaching patterns can be found in Table 9.

Participant	Pre-Intervention	Post-Intervention
1	R-R-R	R-R-R
2	R-R-R	R-R-R
3	R-R-R	R-R-R
4	R-R-L	R-R-L
5	R-R-R	R-R-L
6	R-R-L	R-R-L
7	R-R-R	R-R-R
8	R-R-L	R-R-L
9	R-R-L	R-R-L
10	R-R-R	R-R-R
11	R-R-R	R-R-R
12	R-R-L	R-R-L
13	R-R-R	R-R-R
14	R-R-R	R-R-L
15	R-R-R	R-R-R

Table 9 - Participant Reaching Patterns for Positions 1, 2 and 3, Respectively

These findings indicate that environmental cues (in this case, the initial placement of the pitcher) may afford for the desired behaviors when users are recovering from an injury and should not be using their injured hands, but it is more likely that they will use their injured hand anyway. In order to prevent this behavior, in scenarios where environmental cues are not enough to deter patients from using their injured hands, products may have to make tasks impossible to be done with an injured appendage. For example, using the pitcher, if the space between the pitcher and handle was large enough for a hand but too small for a hand in a cast, users would be unable to pour water with their injured hand. Users may attempt to begin the task with their injured arm or hand, but they will not be able to complete or carry out the task without switching to their uninjured hand. This is just one instance in which a small design change can elicit safer behavior.

Postures captured from the scans during the pouring task showed compensatory movements including extreme (significantly different) shoulder ad/abduction, shoulder flexion/extension, internal/external rotation of the shoulder and flexion/extension at the elbow. Lateral trunk bending was also observed. It is possible that this lateral bending explains why internal and external shoulder rotation changes were not as significant as some other changes in posture.

The container opening task showed that 0% of participants used their non injured, non dominant hand to open the container. With all the majority of the participants (100%) attempting to use their casted, dominant, hand, it may be concluded that having fewer indentations around the lid corners of the container could afford for less opportunities in different ways that the lid can be removed. Though all the participants used their dominant hand to open the container, participants found various different methods for removing the lid. This was fine for the purpose of this study as this component involved comparison of the same participant before and after the addition of the cast. Figure 9 show an example of two very different, but ‘wrist neutral’, with wrist extension at less than 15° (RULA, 1993), approaches for removing the lid from the container.

Figure 9 - Wrist Neutral Lid Removal Approaches

Two other variations were found in the lid removal task before the forearm splint was even placed and can be seen in Figure 10. These postures more actively engaged the wrist with the first image showing wrist flexion and the second showing wrist extension.

Figure 10 - Active Wrist Lid Removal Approaches

One particularly unique approach for lid removal involved a pinching and peeling type movement that the participant maintained after the placement of the forearm splint which can be seen in Figure 11. In this instance, the participant, after losing the ability to flex the wrist, compensated with extreme scapular retraction and shoulder abduction.

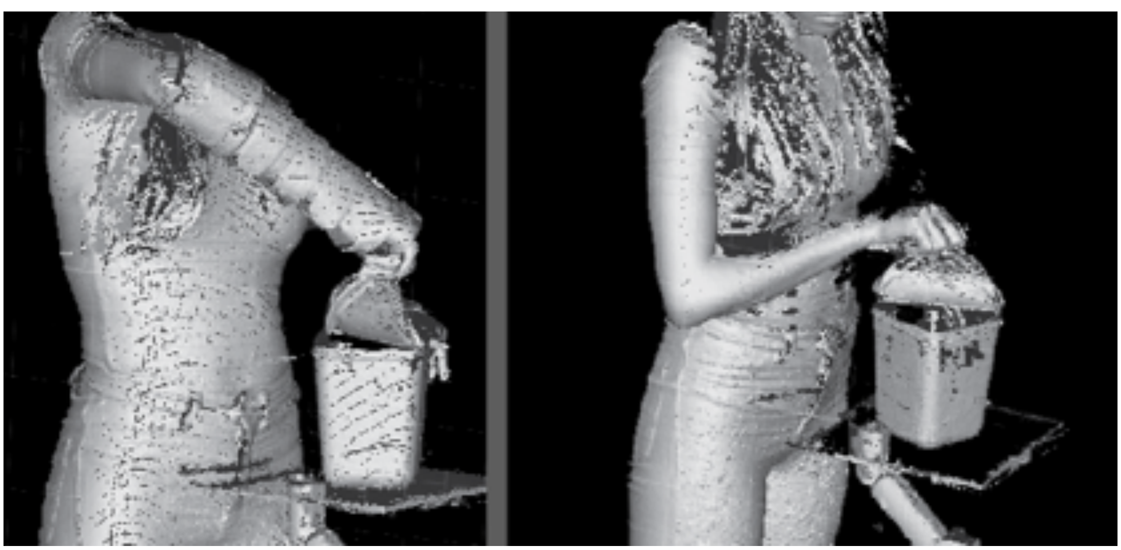

Figure 11 - Best Example of Compensatory Behavior Change on Lid Removal Task

The observed participant performance on these tasks echoed the aforementioned kitchen behaviors correlated with kitchen accidents (Preparation, Makes use of correct tools, Unsanitary practices, Unsafe practices, Safe practices, Fails to follow directions) as described in Guilford (1973). Participants expressed that it was more difficult to pour with the splint than it was without the immobilization device, thus making preparation and correct use of tools difficult. Participants frequently used their casted hand, which in a real life application and a hard cast could have implications of infections or irritation (Delasobera, 2011).

Several participants noted that had the pitcher been completely full, they would have been afraid to lift the pitcher, or spill the pitcher, potentially making the act of pouring unsafe (either by dropping the pitcher, creating a spill or straining themselves). Additionally, at least two participants, commented that they had made a "bad decision" after reaching for the pitcher with their injured, dominant, hand.

Awkward Postures

The awkward postures were determined as being outside of the neutral reference postures outlined in Human Factors and Ergonomics Society Thresholds for Risk. These neutral posture ranges are summarized in Table 2 along with a diagram of the movement. Participant postures while "injured" were compared to their baseline postures that showed their natural behavior without a cast or simulated injury. The paired t-test indicated that there were some significant ($p < 0.05$) changes in they ways participants moved to complete the tasks.

For the pitcher tasks, before even beginning to pour, these significant changes occurred in shoulder abduction/adduction (p =0.026), shoulder flexion/extension (p =. 033), internal/external rotation at the shoulder (p = 0.032) and elbow flexion/extension (p=0.000). The act of pouring most affected shoulder abduction (p = 0.009) and shoulder flexion/extension (p = 0.012).

Joint and Movement:	***Shoulder Abduction***	***Shoulder Flexion***	***Internal Rotation at the Shoulder***	***Flexion/ Extension at the Elbow***
Angle:	20 degrees	25 degrees	0 degrees	70/135 degrees
Reference:	*ANSI/HFES*	*ANSI/HFES*	*Kapandji, 1970*	*ANSI/HFES*
Diagram:				

Table 2 - Threshold for Awkward Postures Listed by Joint, Direction of Movement and Angle

The lid removal task also showed signs of compensatory behavior, with significant changes in shoulder flexion/extension (p = 0.052) for the starting position and changes in shoulder ab/adduction (p = 0.012) and shoulder flexion/extension (p = 0.004) when removing the lid from the container. It is clear that the placement of the brace promoted changes in behaviors and postures across the participants.

Unanticipated Observations

Though not originally an area of desired exploration, it was observed that grip and pinch strength were not as strong when the dominant (right) hand was measured with the forearm splint applied. This may be an interesting area for future investigation as originally it was perceived that the forearm splint may have caused the participants to be subconsciously malignant (Aronoff, 2007) and / or could be exhibiting early signs of learned helplessness (Lindroth, 1994) which could be magnified in the case of a patient with a real injury and cast. Having even further reaching implications, this concept could be especially important regarding elderly with limited mobility and dexterity or those facing permanent immobility.

Upon further investigation it became more clear that the 35.34% decrease in grip strength seen in all the participants was because of the participants' inability to contour their grip to the Hand Dynamometer with the hypothenar eminence and additionally lose help from the thumb. The splint also prohibits the use of flexor digitorum superficialis, the lumbricals and the dorsal and palmer interossi (Nordin and Frankel, 2001). Participant pinch strength was not significantly decreased.

Limitations

While this study involved the use of an empty pitcher to simulate a pouring task, it would be of value to conduct this study with a weighted pitcher to mimic a more realistic scenario. Due to the preliminary nature of this study, and our lack of knowledge on how participants would change their behaviors, it was in the best interests and safety of the participants to only simulate a pouring task as to not strain participants' non-dominant or casted arms during the study. This is magnified even further by the fact that even with prescribed tasks, participants still reacted in many different ways, making it unclear how persons in a real life setting would react to activities of daily living.

Sample size was also a foreseen limitation, as the time and funding for this study were limited. However, with the small sample size in mind, great precautions were taken to reduce within group variability by controlling for handedness, previous injuries and sex.

It is also important to keep in mind that the participants in this study were pain free and relatively (musculoskeletally) healthy at the time of the study. As a result, no additional side effects of a real injury were present such as blood, bruises or soreness. This study is however representative of functional limitations about 5 - 6 weeks into the healing process. This time observes a critical window where people are feeling "better" but could potentially re-injure themselves or increase the amount of immobilization time needed.

CASE STUDY

Two participants were chosen to show approximate boundaries of performance for the sample. The low performer represents the lowest boundary of performance while the high performer represents the highest boundary of performance. These participants serve as an example to highlight the the best and worst case scenarios for dexterity in real patients following an injury.

Based on the verbal categories available form the PP and MMDT, “high performing” and a “low performing” were able to be selected from the sample to observe and compare their differences in performance across the standardized dexterity tests as well as the kitchen tasks. The “high performer” was selected based on their consistently above average performance across all the manual dexterity tests with or without the forearm splint. The “low performer was selected based on their consistently below average performance across all the task. Participant 2 was selected as a low performer while Participant 9 was selected as a high performer. A side by side comparison of their performance on the Manual Dexterity Tests can be seen in Figure 12 for the MMDT and in Figure 13 for the PP.

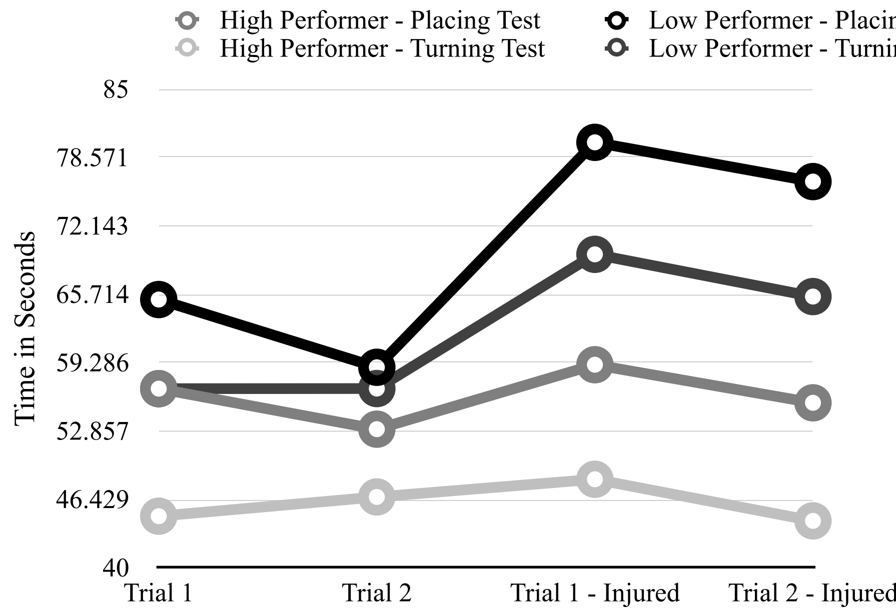

Figure 12 - Comparison Across all MMDT Tests and Trials for High and Low Performer

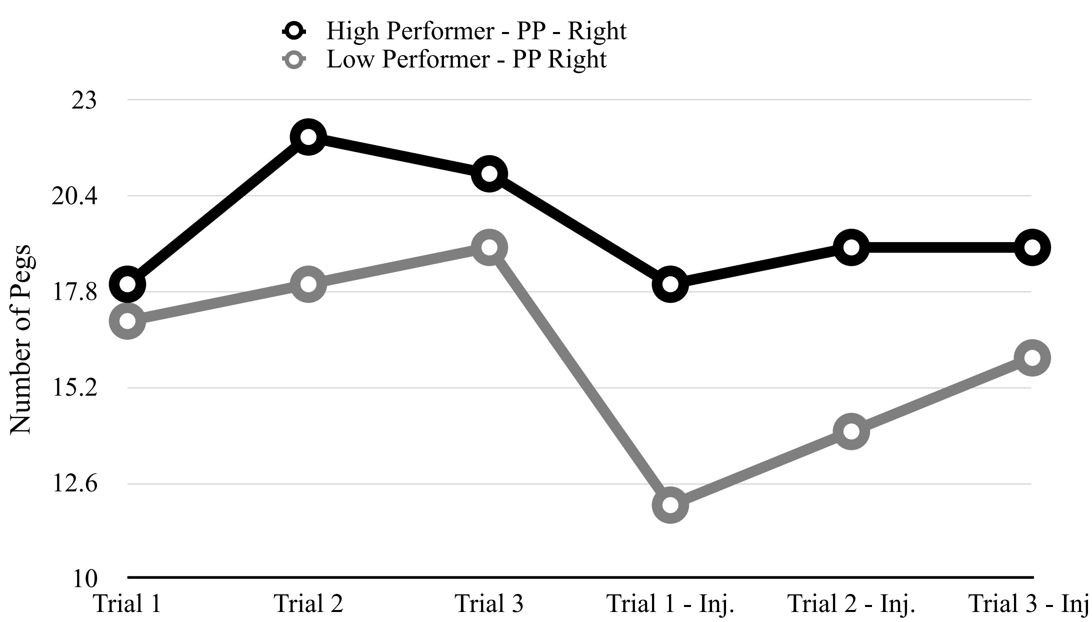

Table /Figure 13 - Comparison Across all PP Tests and Trials for High and Low Performer

High Performer

Participant 9 displayed excellent performance across all the manual dexterity tests. It is also noteworthy to mention that this participant's reaching patterns were R-R-L before the placement of the splint and remained R-R-L after the intervention. This high level of dexterity may be the reason this particular participant was more receptive and could more easily adapt to the changing environmental cues presented in the pitcher task. It would be beneficial for future studies to examine this hypothesis, as it could shave a large impact on patient care and advice following an injury.

Low Performer

In contrast, Participant 2 performed poorly across the MDTs before and after the placement of the splint. The reaching patterns for this participant were R-R-R before the intervention and remained R-R-R afterwards. While a little over 50% of participants in the study showed R-R-R reaching behaviors after the placement of the splint, studying this specific instance may best illustrate the inability to quickly change the way in which a task is approached.

Comparison

Adult norms for grip strength indicate that the mean grip strength for women aged 20-24 is 70.4 pounds (Mathiowetz, V., et al., 1985). It is interesting to note that the low performer had a grip strength of 62.5 pounds before the intervention, about half of a standard deviation below the mean for normative grip strength (SD =14.5). The high performer on the other hand was nearly a whole standard deviation above the mean with a grip strength of 84.167 pounds. While grip strength was not a reliable indicator for performance on dexterity tests (as strength and dexterity are separate components of task completion) this was another notable difference between the two selected participants.

Tip pinch strength also reflected a similar pattern. The mean tip pinch strength for women aged 20-24 was 11.1 pounds (SD=2.1). The low performer, with a pinch strength of 7.830 fell about 1.5 standard deviations below the norm for women in her age category. The high performer's pinch strength was nearly average, with a tip pinch of 11.667 pounds.

The most notable difference between participants occurred when the pitcher was placed in position 3. Following the intervention, in starting position 3, the low performer exhibited shoulder abduction of 30 degrees while the high performer only abducted the shoulder 10 degrees. In comparison to the entire sample, the mean abduction for this position was 11.3 degrees (SD = 0.9). Shoulder flexion in this position was also highly variable. The low performer had the second largest flexion of the entire sample with 49 degrees (the highest being 50). The high performer did not show any measurable signs of flexion, with the mean for this measurement being 12.93 degrees (SD = 1.056).

When using the right hand to pour, the low performer abducted their shoulder 28 degrees pre intervention and 76 degrees post intervention (M = 43.767, SD = 1.768 for pre intervention and M= 65.133, SD = 2.157 post intervention). The high performer abducted their shoulder 15 degrees and then 18 degrees post intervention.

Data is not available for the low performer in the left handed pouring task because the low performer used their right hand for this task. The the high performer, consistent with other observations, performed at or slightly below the mean before the intervention. It is interesting to note that after the intervention, pouring with the left hand lead to abduction of the shoulder at 55 degrees while the mean was only 41 degrees (SD = 2.864). Both the mean and the high performer’s measurements were in the awkward range for shoulder abduction as defined by HFES/ANSI (> 20 degrees) but can likely be explained by the fact that all the participants were right hand dominant.

Knowing this information about a patient following an injury could alter the way their Physical Therapy is strategized or help doctors to recommend changes in the home following an injury to facilitate ADLs.

CONCLUSIONS

The time needed to complete both the standardized dexterity tests as well as the simulated kitchen tasks increases following the implementation of the forearm brace

Analyses of the data from this study indicate that there is a significant increase in the time needed to complete rudimentary tasks in the kitchen after being placed in a forearm splint or cast. Participants frequently engaged in behavior that would be considered unsafe in an uncontrolled environment and it was observed that participants often reacted in ways that were most convenient (as opposed to the safest methods) for completing the task at hand. Behavior as such would likely have many negative implications on users facing real forearm injuries or breaks in an uncontrolled environment.

Participants need to change their regular behaviors after losing full range of motion and are more likely to use their injured, dominant hand

Awkward postures were prevalent in both the MDTs and kitchen tasks. Participants exhibited instances of compensatory behavior though some of the changes were not significantly different. The changes in posture may be enough to re-injure a healing limb or strain a muscle group that is not frequently employed by the user in a situation or environment that is not controlled.

Participants were more likely to use their injured hand in almost all of the simulated kitchen tasks. 100% of participants used their right hand in lid removal, 100% used their right hand to pour from positions 1 and 2. Over 50% used their right hand to pour from position 3.

Environmental cues do not have a strong enough impact on users' decision making behaviors

It was initially postulated that environmental cues would have a significant impact on which hand participants would use to complete the proposed tasks. It was clear that while using their injured, dominant hand, was the most time consuming and difficult way to do things, it was still the primary reaction when being asked to complete a task. In this study, the environmental cues were not strong enough to guide the participants' behaviors. As previously mentioned, after completing a task with their injured dominant hand, several participants noted that they had "made a bad choice" or that "this was a bad idea". This may be important information for real injuries to the upper extremity scenarios where a bad decision could lead to further injury because of an impulsive reach, grab or movement. Applying this information to an injury recovery timeline could be crucial to patient healing time.

FUTURE AREAS FOR STUDY

This was a preliminary study which may be the precursor to design interventions in the kitchen and home or a potential alteration in the way limbs are immobilized to facilitate activities of daily living. With this study, some reference postures following a forearm injury have been established using healthy participants simulating an injury. Following a similar method of this study, other injuries and immobilization devices would be beneficial to examine for the future. With the high correlation of forearm and hip fractures, studying the lower extremity may be crucial as well.

Having now established a baseline of patterned behavior for this small sample, this particular area of study would benefit from larger, similar samples as well as samples that include participants with a history of a forearm fracture. A second valuable pool of participants could stem from children that have not yet broken a bone as they will have even fewer conceptions of how kitchen tasks should be conducted and will perhaps respond even more intuitively than young adults.

The case study revealed that grip and pinch strength may have an influence on performance. Participants with grip and pinch strengths closer to the normative average tended to complete the kitchen tasks in a safer manor than participants with low grip and pinch strength.

A longitudinal study following patients from injury through recovery would also answer many questions unanswered by this study. It would be particularly interesting to establish a “healing timeline” to measure peoples functional capabilities against their expectations and needs.

Investigation into the design of immobilization devices could prove to be helpful in developing casts that even further limit the movement of use of an injured limb until a certain time in the healing process, when appropriate. If patients are given the opportunity to move and use part of their injured extremity, will they take it too soon too far?

Environmentally, it may be of value to study if there are ways to arrange our home following an injury that help to remind injured users to not put themselves in potentially dangerous, awkward postures in order to complete activities of daily living.

Future areas for study would also benefit from exploring more activities of daily living to begin establishing baseline values for ADL similar to those of manual dexterity tests (perhaps based on similar biomechanical movements).

To minimize risk of injury for this study, simulated kitchen tasks needed to be observed (as opposed to actual ADLs). Adding weight or real liquids to the pitcher could have resulted in injury as it was unknown how the participants would react after being put in a cast. Studies that closely follow someones daily routine and perhaps actual tasks would be most beneficial in coming research.

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