Objective Evaluation of Fine Motor Manipulation of the Hand in Normal Participants

by

Elizabeth R. Andersen Hammond

A Thesis submitted to the Faculty of Graduate Studies of

The University of Manitoba

in partial fulfillment of the requirements of the degree of

MASTER OF SCIENCE

School of Medical Rehabilitation, Faculty of Medicine

University of Manitoba

Winnipeg

August 2007

THE UNIVERSITY OF MANITOBA

FACULTY OF GRADUATE STUDIES
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MASTER OF SCIENCE

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ABSTRACT

Purpose: To develop a tool that accurately and precisely evaluates a component of fine motor hand function during manipulation of any object. For clinical comparison, performance with this tool was compared to four commonly used tests of fine motor dexterity. Reliability was established and movement accuracy was compared between two conditions, normal manipulation and a simulated index finger amputation.

Participants: Twenty right handed participants (ten males, ten females, age 24-47 years) were recruited from a sample of convenience.

Methods: The Minnesota Rate of Manipulation Test (MRMT), Purdue Pegboard, O'Connor Tweezer Dexterity test and Nine Hole Peg test were administered to each subject without the use of the index finger to simulate an amputation. Three objects, ranging in weight and size which required the use of 2 or 3 fingers were selected for this study. Motor performance was then quantified during manipulation using a computerized visual guided tracking task and the miniBird (Ascension Technology, Burlington, VT, USA) miniature motion tracking sensor. Subjects performed the test with and without the use of the index finger. A computer cursor cued participants to move the object in a sinusoidal trajectory with the amplitude and frequency selected to match normal function. An electro-goniometer (Biometrics Ltd., Gwent, UK) was attached to record wrist motion. To establish the test retest reliability the protocol was repeated one week later.

Analysis: The actual sinusoidal object movement was compared to the reference cursor trajectory for each object and test period (cross-correlation). Temporal accuracy and amplitude consistency was evaluated for each trial. Wilcoxon signed rank test was used to determine test retest reliability and evaluate changes in accuracy between the two conditions. Spearman rank correlation was used to test for correlations between the common dexterity tests and the task protocol. Results $p<0.05$ were considered significant.

Results: The test protocol reliably quantified movement accuracy at both time periods. No significant differences were found between time one and time two for the cross-correlation, temporal accuracy and amplitude consistency data. No positive correlations were found between the clinical dexterity tests and the task protocol. The pen task demonstrated statistically significant differences on the cross-correlation when the two conditions (normal and simulated amputation) were compared with the normal condition providing more accurate results ($p=0.033$). The pen task also demonstrated differences for the temporal accuracy within the normal condition ($p=0.003$). The wine task showed significant differences in amplitude excursion between the two conditions with the simulated amputation condition producing more motion ($p<0.001$).

Conclusions: The task protocol directly measures the ability to manipulate three objects in response to a visual tracking target. Both temporal accuracy and amplitude consistency can be evaluated. The current study confirmed the test retest reliability of three objects. The commonly used clinical tests were either unrelated or negatively related to the protocol indicating that different aspects of hand function were being measured. Development of this tool is important for hand therapists, not only as an assessment tool, but also as an outcome measurement for treatment and research.

ACKNOWLEDGEMENTS

This thesis would not have become reality without the help, suggestions and guidance from my advisor, committee, colleagues, friends and family.

First, I would like to thank my advisor Dr. Barbara Shay for being my mentor and allowing me to create my own research project and protocol. Your guidance and feedback was invaluable to direct and often re-direct my thoughts at times. Likewise, I am grateful to my co-advisor, Dr. Tony Stzurm for conversations that clarified my thinking on motor control, data collection and analysis. Next, I would like to thank Dr. William Rennie who immediately agreed when I asked for his assistance. Your expertise, support and advice were greatly appreciated.

To my colleagues and students in the lab, thank you for being my guinea pigs and making the matlab problem solving less tedious. To my colleagues at PAR Health Services, your suggestions and support were instrumental in developing my protocol.

To my friends, particularly Shelley for understanding my academic pursuits and to Angelique who kept me healthy with those long runs.

At this point, I would like to thank my family who are the most important part of my life. To my mom, who often had mother/daughter time postponed in order to meet looming deadlines. You always understood and encouraged me when it was most needed. Thanks to my cat, Tio, for her valiant efforts in typing. To my husband, Allan, you always knew what I needed, whether it was focused, uninterrupted work or time to procrastinate.

Thank you all

Dedication of this thesis is to my father, who is sadly missed in sharing this personal accomplishment.

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INTRODUCTION

The goal of rehabilitation is to make functional improvements in the lives of patients. The goal of hand therapists is to restore the hand and upper limb to its highest functioning level after an injury. Therapists need to quantify hand function to plan treatment, evaluate the effectiveness of treatment, provide appropriate adaptive equipment, and outline job restrictions to third party payers and employers. To date, therapists have relied on timed tests and observational grading of tasks to evaluate the hands' ability to manipulate objects.

Commonly used standardized tests to measure fine motor dexterity in the hand include: the Purdue Pegboard, Minnesota Rate of Manipulation, Nine Hole Peg Test and O'Connor Tweezer Dexterity Test. These tests are quick and easy to administer, and may be viewed as representing some general ability to perform functions relating to fine motor tasks. Some authors (Bear-Lehman J., 1989;Kimmerle, 2003;Rice et al., 1998) have argued that the time scores obtained do not describe the ability of the hand to function at work or in daily life.

All four of these commercially available tests use speed to imply a level of performance when compared to age matched norms. While it is recognized that time is an important component in efficient object manipulation, these tests do not directly measure the accuracy of finger movement or grade the fluidity or consistency of movement. In addition, the objects are limited to pegs or disks which represent only a small subset of objects that are manipulated in daily life.

Many of these tests were originally developed as a screening tool for work in industrial jobs requiring fine motor dexterity. The normative data generated from industrial employees makes it inappropriate for comparison and difficult to generalize to patient populations (Bear-Lehman J., 1989;Rice et al., 1998). The hand therapy literature identifies that these tests are limited to repeated insertion actions while ignoring the more challenging motor control and planning movements (Kimmerle, 2003). Hand therapy research has outlined a variety of ways to attempt to include these complex motor patterns in a hand assessment with different models and frameworks (Kimmerle, 2003;Rudman, 1998). However, as the assessment models are not standardized outcome measures, this remains a problem.

A more useful comparison for scoring function after hand injury would be to use criterion referenced values. Criterion referenced values provide a baseline score for each task. This score reflects a basic functional requirement to effectively complete the task. While the need to develop criterion referenced scores is well known, very little research has been performed on these tests relating to hand injuries (Apfel and Carranza, 1992).

Grasping, transporting and manipulating objects with the fingers and hand are complicated interactions which have attracted considerable scientific attention in the areas of neuroscience, motor control and robotics (Carey et al., 2002;Dipietro, 2003;Flanagan et al., 1999;Mason et al., 2001;Pataky et al., 2004;Talati et al., 2005;Zatsiorsky et al., 2003). Studies have used a variety of technologies to quantify motion and forces including: an electro-goniometer attached to the finger to record accuracy in tracking a computer sine wave (Carey et al., 2002), instrumented gloves that measure joint finger motion (Dipietro, 2003), 3D digital motion analysis systems (Mason et al., 2001), and instrumented objects with pressure sensors to detect object contacts (Zatsiorsky et al., 2005). These studies provide methods of finger hand function evaluation.

The current clinical tests of fine motor dexterity, while helpful, cannot assess the fine motor control of the hand injured patient. There is a need to develop an assessment tool and outcome measure that can quantify fine motor manipulation. A tool that quantifies the accuracy of the fingers while manipulating virtually any object would assist hand therapists in planning and evaluating treatment, in addition to providing a much needed objective outcome measure for research. The purpose of this research is to develop a tool that will accurately and precisely evaluate a component of fine motor finger/hand function and establish test retest reliability.

LITERATURE REVIEW

The functional importance of the hand seems obvious when one thinks of daily activities such as dressing, grooming, eating, handling objects, playing musical instruments, or fulfilling virtually any job demand. The hand is also important in gesturing, displaying emotion, and communication for the blind and deaf. While all of these functions are important, Tubiana identifies the most crucial functions being that of the sensory function of touch and prehension. Prehension has been defined as "all the functions that are put into play when an object is grasped by the hands - intent, permanent sensory control, and a mechanism of grip" (Tubiana, 1984)

Prehension

Prehension consists of several phases: approach, grip and release. Approach involves the trajectory of the hand towards an object and this can be accomplished by vision, palpation, or memory. Grip consists of opening the hand, closing the hand around the object and regulating force. Release requires simultaneous action of intrinsic and long extensor muscles (Tubiana, 1984). These prehension stages are involved for all types of grip including the postures commonly adopted for tasks involving fine motor manipulation. Fine motor manipulation usually involves the thumb, index and long finger for various pinch postures including;

1. Precision Pinch (terminal pinch) – tip of thumb to tip of index finger with the distal interphalangeal joints flexed, as in picking up a paper clip.
2. Oppositional Pinch (subterminal pinch) – pulp of the index and thumb are brought together with the distal interphalangeal joints extended, as in pinching a straw.
3. Key Pinch (lateral pinch) – thumb is adducted to the radial border of the middle phalanx of the index finger, as in turning a key.
4. Tripod pinch – thumb pulp opposes the pulps of both the index and long fingers, as in writing.

Functional Importance of the Digits

Researchers have attempted to grade the functional importance of each digit and outline the basic requirements needed after a traumatic hand injury (Cheng et al., 2004;Jones et al., 1982;Soucacos, 2001;Soucacos et al., 1994). This helps to provide guidelines to surgeons when presented with difficult cases where the prognosis is often unknown. The basic requirement after a mutilating hand injury is to have a stable wrist and at least two fingers that can oppose. In order to provide superior function over a prosthesis these fingers must be sensate and pain free (Moran and Berger, 2003).

The thumb is of primary importance as it functions in all types of grasp (Bueno, Jr. and Neumeister, 2003;Moran and Berger, 2003;Tubiana, 1984). The thumb has the ability to oppose all digits and the palm and its strength and mobility make up 40% of hand function in an uninjured hand. This can increase to account for greater than 50% of hand function after mutilating hand trauma (Moran and Berger, 2003).

In the uninjured hand, it is thought that the index finger ranks second due to its strength, ability to abduct, relative independence compared to the other digits and its proximity to the thumb (Moran and Berger, 2003;Tubiana, 1984). Despite its importance, the index finger is seldom replaced after finger amputation. The long finger compensates and replaces the index finger in precision pinch with minimal loss in hand function (Moran and Berger, 2003;Zachary and Peimer, 1997).

The long finger has the most strength of the fingers in flexion and its central position allows for function in both precision and power grasps (Moran and Berger, 2003).The ring and little fingers function mainly for power grasp. When faced with a mutilated hand trauma, some authors believe that replanting the fingers to the ulnar border of the hand rather than the radial border is more functional. It is felt that it is important to maintain the span of the palm while maintaining the ability for precision pinch and power grasp (Wei and Colony, 1989). Tubiana believes that the role of the small finger in power grip, ability to expand the span of the hand with abduction and its ability to rotate 25 degrees at the carpal metacarpal joint make it the second most important digit rather than the index finger (Tubiana, 1984).

Hand Trauma Literature

An interesting study surveyed 183 surgeons with finger amputations. Out of 183, only four surgeons needed a career change due to inability to perform required tasks (Brown, 1982). The conclusion was that the motivation of the patient was a more important predictor of function rather than the actual number of digits involved in the injury. Clearly, motivation is a key factor in rehabilitation from hand injuries; however, physical limitations will impact function to some degree. When physical constraints remain, it is whether or not the patient can compensate and adapt to the changes that is influenced by motivation.

The hand and wrist complex is comprised of 27 bones, and a complicated fibrous skeleton. Eighteen intrinsic muscles and thirteen extrinsic muscles produce motion in the wrist and allow movement in the 17 mobile articulations of the digits (Moore and Dalley, 1999;Tubiana, 1984).With respect to hand injuries, the inability to accurately manipulate objects may be due to nerve damage, direct injury to muscle, sensory loss, scar adherence preventing the glide of the tendons, ligament instability, bony deformities, loss of digital length from fractures or re-plantations, fusions, cold intolerance, hypersensitivity or chronic pain. After digital amputations and mutilating hand injuries these problems limit the hand in performing functional tasks.

Injuries to the hand and fingers comprise nearly one quarter of all work-related injuries according to statistics provided by the Workers Compensation Board of

Manitoba (WCB) (Workers Compensation Board of Manitoba and Manitoba Labour and Immigration, 2005). From 2000 through to May 2007, there were 25,799 hand and finger injuries in Manitoba (unpublished statistics provided by the Workers Compensation Board of Manitoba). Of the time loss claims reported, trades, manufacturers, and the service industry account for 72% of hand and finger claims. From 2000 to May, 2007, WCB has paid 46.6 million dollars in time loss claims for hand injuries alone.

With respect to injuries involving traumatic amputation, in the past, survival of the replanted digit marked success of a surgery. In more recent times, return of function guides treatment and determines success (Bueno, Jr. and Neumeister, 2003;Jones et al., 1982;Peimer et al., 1999). Functional outcomes reported in the surgical literature include return to work, strength, range of motion and sensory testing (including Semmes Weinstein Monofilament testing and two-point discrimination) in addition to subjective patient reports. Timed dexterity tests used in the literature to evaluate the hand after digital re-plantation include the Nine Hole Peg Test and modified Moberg test (Jones et al., 1982;Schenck, 1984). Functional measurements in the surgical literature use the same tests that are reported in the rehabilitation literature.

In order to evaluate functional loss, research has been conducted where hand injuries have been simulated in normal participants (Pennathur, 1999;Rondinelli et al., 1997). One study immobilized the 1st carpal metacarpal (CMC) of the dominant hand with a splint. In order to fully immobilize the CMC it was necessary to partially immobilize the 1st metacarpal phalangeal joint, wrist, and forearm. The American Medical Association (AMA) Guidelines rate this injury as moderate impairment. Results showed that despite a moderate impairment rating, participants were able to overcome loss of strength and range of motion to perform most complex functional tasks within the normal/low normal range. They concluded that "impairment rating is a poor estimator of functional loss in the hand" (Rondinelli et al., 1997).

Another study simulated finger amputation injuries and evaluated performance on numerous standardized tests including dexterity and lifting tasks. The simulated injury was extreme, all four fingers on the dominant hand and the thumb in the non-dominant hand. Not surprisingly, they concluded that simulated finger injuries led to a decline in the functional capabilities of the participants (Pennathur, 1999).This study unfortunately provides little advancement in understanding function as one would expect a decline in ability with such an extreme simulated injury.

Individual motion of the digits has been studied/assessed. The thumb, index and little finger were found to be more highly individuated than the long or ring fingers (Hager-Ross and Schieber, 2000). Results from this study would suggest that simulating injuries to the thumb, index or little fingers would be more appropriate as the remaining digits would be less influenced. One must be cautious when drawing conclusions from simulating injuries, as the hand operates as one functional unit. Further, the ability to retrain the hand after injury is a variable that can impact overall results by overestimating impairment. Simulated injuries are helpful in research as the same impairment can be applied to all participants minimizing the confounding variables that would occur with a real patient population.

Rehabilitation Literature

Much of daily life requires manipulation and handling of objects, many of which require a high degree of precision and are often unstable. The term "instability" refers to the fact that small deviations from the correct behavior of the manipulated object leads to complete disruption of performance. Handling silverware and cups, writing, replacing light bulbs, using a toothbrush, and handling coins are tasks that require one to cope with some degree of instability in the manipulated object. Individuals with hand injuries may face these challenges.

Hand Assessment

Typical hand assessment following trauma includes goniometric measurement of range of motion as well as dynamometer measurement of pinch and grip strength. Protective and functional sensory status is evaluated using pressure aesthesiometers (monofilaments) and static and dynamic two point discrimination (Bucher, 2002). Hand edema is measured with volumeter and circumferential measurements. In the acute post operative phase a detailed wound assessment, vascular assessment and description of hand appearance and resting posture is completed. Quantifying hand function has traditionally used therapist observation and timed tests of dexterity including; the Minnesota Rate of Manipulation, Purdue Pegboard, Nine Hole Peg Test, and O'Connor Tweezer Dexterity Test. Since these tests are commonly used to evaluate hand function in the clinical setting, they are described in further detail.

The Minnesota Rate of Manipulation

The Minnesota Rate of Manipulation Test (MRMT) was originally developed in 1933 and since has undergone numerous revisions leading to the commonly used 1969 edition. This test was designed to provide employers with a screening tool for potential employees for jobs requiring arm and hand dexterity. There are five test subsets with the 'placing test' and the 'turning test' being most commonly used. The 'placing test', the 'displacing test' and the 'one hand placing and turning test' use one hand, while the 'turning test' and the 'two-hand turning and placing test' require both hands. All of these tests are scored on the time it takes to complete each trial. The manual recommends four trials of each test for greater reliability. In 1957, norms were revised for the 'placing test' and 'turning tests' generated from 11,000 young employed adults with a median age of 19 years. The manual suggests that this normative data is more suitable for younger adults (Examiners Manual, 1969).

One study evaluated the ability of the MRMT to assess permanent disability of the hand compared to impairment rating scales. The MRMT was administered to 118 patients, excluding the turning test subset. The authors found that the impairment rating scales provide a gross measure of disability and the MRMT "provides a limited but better-defined assessment of hand impairment" (Gloss and Wardle, 1982).

O'Connor Tweezer Dexterity Test

The O'Connor Tweezer Dexterity Test was developed by Johnson O'Connor in 1926 to screen applicants for jobs requiring a high degree of precision. The test uses tweezers as an implement to place pins in a board. The time required to fill all 100 holes with pins completes the test. Norms were developed from workers employed in fine instrument assembly; however, norms have not been developed for the average population (Examiners Manual, 1926).

The Nine Hole Peg Test

The Nine-Hole Peg Test (NHPT) is the most frequently used upper limb function test in the United Kingdom and is widely used in North America as well (Turner-Stokes and Turner-Stokes, 1997). Originally developed in 1971, the Nine-Hole Peg Test was ranked highest in support of psychometric properties when compared to many other commonly used assessment tests of upper extremity function after stroke (Croarkin et al., 2004). Results demonstrated that following stroke, this was the only test of the upper extremity that met three of the four psychometric properties, including concurrent validity, intra-rater reliability, and test retest reliability.

This test measures the time to insert and remove nine pegs from a board. Norms were developed by Mathiowetz in 1985 (Mathiowetz, 1986) and repeated by Oxford in 2003. As the testing dimensions and materials of the board have changed, this latest study compared these results to the original norms (Oxford, 2003). The authors concluded that both versions yielded similar results confirming that the normative data supplied by Mathiowetz remains applicable, despite changes in the pegboard.

Purdue Pegboard

The Purdue Pegboard was first developed by Joseph Tiffin in 1948 to screen employees for industrial jobs such as assembly and packing. Both gross hand dexterity and finger dexterity are measured with the test. Five subsets are included involving 'left hand', 'right hand', 'both hands', 'right and left and both hands', and 'assembly'. For the right hand test, pins are inserted into the pegboard and the number of completed pins in 30 seconds is added for scoring. Three trials are administered. Research evaluating the retest reliability found that three trials produced the most reliable scores and therapists should be cautious if interpreting single trial scores (Buddenberg and Davis, 2000). The original norms were based on employees and applicants for these positions (Instruction Manual, 1948). Since then the manual provides normative data for children with learning disabilities, language disorders, brain injury, and vocational rehabilitation assessment. Not surprisingly, validity studies of the Purdue Pegboard to assess patients after hand trauma found that this test can differentiate between hand injured and healthy individuals (Ben, 1998).

All four of these commercially available tests use time to evaluate function. Time is not the only variable required to assess fine motor hand function. The pins, pegs and discs manipulated represent only a small portion of the objects used in daily life. Furthermore, these tests measure only simple grasp and transport functions and do not evaluate the complex motor control demands needed for hand function.

Motor Accuracy Literature

Research into the accuracy of human hand movement has involved many disciplines including psychology, neuroscience, physiology, biomechanics, robotics and rehabilitation. How the hand grasps and manipulates objects by producing postural synergies and controlling forces is beginning to be understood in the normal human hand. Evaluation of motor impairment and the ability to restore function of the arm after cortical injury has generated research in stroke, spinal cord injury and brain injured patients (Carey et al., 2002;Memberg and Crago, 1997;Yamanaka et al., 2005), but insights into hand function after a musculo-skeletal hand injury remains poorly understood. Understanding the neuro-musculo-skeletal components "will be instrumental to preserve and restore manual ability in people suffering from neurological and orthopedic conditions" (Valero-Cuevas, 2005).

A variety of methods have been used to quantify hand and finger function including, motion analysis, electro-goniometers with visual tracking targets, electro-magnetic sensors, instrumented gloves with force sensors and goniometers, and instrumented objects with accelerometers and force plates (Carey et al., 2002;Degeorges et al., 2005;Dipietro, 2003;Flanagan et al., 1999;Mason et al., 2001;Memberg and Crago, 1997;Santello et al., 2002;Yang et al., 2002)

These studies have evaluated different components of hand function including: the influence of sensory guidance in shaping the hand to grasp objects (Santello et al., 2002); the ability of the hand to coordinate movement patterns in response to auditory stimuli (Balasubramaniam et al., 2004); hand synergies in reaching and precision grip (Mason et al., 2001); kinematic studies measuring rotations of the digits in flexion

(Degeorges et al., 2005); the ability to use a neuroprosthetic devise after spinal cord injury (Memberg and Crago, 1997); and, fMRI studies to understand the dynamic neural system of hand function post-stroke (Carey et al., 2002;Talati et al., 2005). All of these studies seek to understand the complex interaction between vision, touch, memory, the CNS, forces, synergies, and the biomechanics and anatomy that enable the hand to grasp.

When quantifying motion, studies have used different cues to direct or initiate movement. Some studies use auditory cues such as a metronome or buzzer (Balasubramaniam et al., 2004) while others use visual cues such as computer generated sine waves or figure of eight movements (Carey et al., 2002;Yamanaka et al., 2005). A sine wave is a cyclical movement symmetric in position and velocity ideal for continuous movement tasks (Balasubramaniam et al., 2004). Control of timed repetitive actions, whether the cues are internal, auditory or visual must satisfy two goals, precision and accuracy in timing and organization of movement parameters to meet interval requirements (Balasubramaniam et al., 2004).

Miniaturized position and motion tracking sensors can be used for sensing the three dimensional position of an object over a discrete visual tracking system. Electro-magnetic sensors have been used in hand motion studies to track the three-dimensional position of the wrist during reach (Baud-Bovy and Soechting, 2001;Santello et al., 2002). In particular, the miniBIRD electro-magnetic sensor (Ascension Technologies, Burlington,VT, USA) is extremely reliable and accurately measures the real-time, instantaneous position and orientation of the sensor with six degrees of freedom. Thus, the miniBIRD can sense linear and angular movements in three dimensional space (x,y,z). It allows accurate tracking of the spatial location of any body segment including the fingers or object it is attached to with unrestricted range of motion.

A need for developing an accurate assessment tool to measure function has been identified in the rehabilitation literature. It is known that the current tests are limited in that they offer only a gross estimate of fine motor function (Bear-Lehman J., 1989;Kimmerle, 2003). The engineering, neuroscience, biomechanics and robotics literature has shown that an electro-magnetic sensor (Santello et al., 2002) and visual tracking (Carey et al., 2002;Yamanaka et al., 2005) are valid tools to evaluate the hand. Surgical literature evaluating function after secondary reconstructive procedures from mutilating injuries has been limited to the same outcome measures used in the rehabilitation literature. A tool that could quantify the ability of the hand to manipulate objects would provide more appropriate objective analysis of these reconstructive efforts to restore function compared to the current tests.

As hand therapists, it is important that we are able to objectively grade the performance of fine motor manipulation to measure outcomes after surgery, the ability to safely return to work and confirm the effectiveness of our therapy. At present, a tool that can measure accuracy, consistency and precision in fine motor tasks that is easy to administer and provides reliable information is not available.

PURPOSE, OBJECTIVES AND HYPOTHESIS

Purpose

The purpose of the current study was to develop a functional framework that accurately and precisely evaluates a component of finger/hand function during fine motor manipulative tasks. Further, these tasks related to functioning in activities of daily living. A secondary purpose was to assess the performance using the tool compared to commonly used clinical tests for fine motor dexterity; specifically, the Purdue Pegboard, Minnesota Rate of Manipulation, Nine Hole Peg Test, and the O'Connor Tweezer Dexterity Test.

Objectives

1. To establish the test retest reliability of the task protocol in providing reliable and accurate outcome scores evaluating fine motor manipulation.
2. To correlate movement accuracy (time and relative amplitude) obtained with the miniBIRD to scores obtained by the Purdue Pegboard, Nine Hole Peg Test, Minnesota Rate of Manipulation and O'Connor Tweezer Dexterity Test and establish concurrent validity.
3. To quantify the differences in movement accuracy during fine motor manipulation tasks between two conditions: 1) normal manipulation and 2) simulated index finger amputation.

Hypothesis

1. The task protocol and measurement system will be a reliable measure of fine motor movement accuracy.
2. The movement accuracy will correlate with the common clinical tests; however, the miniBIRD will be more sensitive with respect to accuracy in the time and amplitude domains and overall object manipulation.
3. Objects manipulated in the simulated index finger amputation condition will demonstrate decreased accuracy when compared with the normal manipulation condition.

METHODOLOGY

The following paragraphs provide the details of the participants, study design and the instruments selected for testing fine motor manipulation.

Participants

Twenty right handed participants (ten males; ten females; mean age 34; range 24-47 years) were recruited via advertisement from students and staff at the University of Manitoba and Health Sciences Centre, Winnipeg, Canada. Participants were excluded if there was past history of upper extremity pathology with residual deficits, recent injury to the right arm, cognitive impairment and any history of neurological impairment affecting balance, vision or coordination. Participants were fully informed about the procedure and informed consent was obtained once the participant read the Participant Information and Consent form and all questions were answered.

Power calculation for this study was not performed. Previous research had shown that ten participants provided reliable results allowing credible conclusions to be made (Balasubramaniam et al., 2004;Carey et al., 2002;Dipietro, 2003;Yang et al., 2002;Degeorges et al., 2005).

Study Design

The experimental design for this study used a repeated measures approach. One experimental group was exposed to several independent variables including the tests of dexterity, the objects selected, the specified pinch posture, the path of object motion, and the amplitude and frequency of the waveform. The dependent variables included the accuracy of the task in time and amplitude, the correlation to the clinical dexterity tests, the amount of wrist movement that occurred during the trials, and the chosen start position of the wrist. Participants served as their own control group.

Instrumentation

The task consisted of performing natural movements associated with everyday objects. The object properties that were considered included geometric size and shape, texture and friction. The size and weight of the object was chosen to reflect typical objects that would normally be manipulated with two or three fingers. The three objects selected are as follows:

1. A cork for rotation mimicking any small dial (motion in an angular Z plane)
2. A pen that will push a small wheeled platform forward and back mimicking writing or pushing food on a plate (motion in a linear Y plane)
3. A plastic wine glass rotating the stem of the glass forward and backward (motion in a linear Y plane)

This way, the accuracy of tasks requiring various degrees of precision, different movement strategies and a variety of pinch postures were measured.

ASSESSMENT TOOLS

Electro-magnetic Sensor

The miniBIRD Model 800 DC magnetic tracker (Ascension Technology, Burlington,VT, USA) was attached to the objects being manipulated. A permanent mark was placed on the object to ensure that consistent placement occurred with each trial. The magnet was kept stationary throughout all data collection, subjects were seated in the same position and the object with the sensor was positioned to ensure the direction of motion was consistent across subjects and trials.

The miniBIRD records up to 144 measurements per second when the sensor is within +/-30 inches of the transmitter. The reference frame is aligned with the orientation dimple (black dot on the sensor head) facing up with the cord towards the magnet. In this position linear x,y,and z follow the right hand rule. Orientation angles are defined as rotations about the x (roll), y (elevation), z (azimuth) axes of the sensor.

Electro-Goniometer

The SG65 Biometrics electro-goniometer (Biometrics, Gwent, UK) recorded the range of motion at the wrist using DataLink technology. The goniometer was attached to the back of the hand and distal forearm with double-sided adhesive tape. All participants were reminded that object manipulation was to occur using only the digits. Participants were allowed one trial for practice to find the most comfortable wrist posture. A starting wrist position was not specified so participants could adopt any wrist position that felt most comfortable to them. However, once the trial began the participants were instructed not to move the wrist. Wrist motion was recorded at 100 Hz.

Visual Tracking Task

A computer generated sine wave provided the visual open-loop tracking task. A sinusoidal movement showing a bright red dot appeared on the computer monitor. The participant moved the object in concert with the moving cursor following a linear or angular plane of motion depending on the object being manipulated. The amplitude and frequency of the cursor movement was adjusted to match the objects' natural movement amplitude and speed. For all three objects, preliminary tests showed that ten percent of the height of the computer screen at a frequency of 0.4 Hz felt the most comfortable and normal for participants. These parameters were then selected with a forty-five second duration producing 19 cycles for analysis.

Clinical Tests

The commonly used clinical tests included the Purdue Pegboard Model 32020 (Lafayette Instrument Company), the 1969 edition of The Minnesota Rate of Manipulation, placing and turning sub-sets (Western Psychological Services), the O'Connor Tweezer Dexterity Test Model 32022 (Lafayette Instrument Company) and the Nine Hole Peg Test (Northcoast version). These tests were administered in accordance with the procedures outlined in the manuals. All participants completed these tests as they would in a normal situation with the exclusion of the index finger to simulate an amputation.

Protocol

The project was approved by the Health Research Ethics Board (HREB), University of Manitoba (H2006:058). All data was collected at the Motor Control Laboratory at the School of Medical Rehabilitation, University of Manitoba. Participants signed an informed consent document if they chose to participate in the study. The informed consent document outlined the purpose of the project, research procedures, and participant expectations. It was made clear that the participant could stop his or her participation in the study at any time.

A screening assessment ensured that each participant had full range of motion of the hand, normal sensibility (using the 2.83 monofilament from the Semmes Weinstein Monofilament Test) and normal visual acuity (tested with eye chart for 20/20) to complete the computer tracking task. In addition, volumeter measurements were taken to measure hand size of each participant. Demographic information was collected including date of birth, participants' full name, and contact phone number.

Initially, two clinical tests were administered excluding the index finger. Four trials of The Minnesota Rate of Manipulation 'Placing Test' were collected. This was followed by three trials of the 'Right Hand Test' for the Purdue Pegboard. The tests followed the guidelines for administering and scoring as outlined in the examiners manuals.

Following the clinical tests, participants were comfortably seated in front of a computer screen. The shoulder and elbow were in a comfortable starting position. A specified shoulder and elbow posture was not given to allow the participants manipulate the objects as naturally as possible. It was emphasized prior to each trial that the wrist should not be used to complete the task. Instead all object manipulations were performed with the fingers. Each participant was allowed one trial to practice the task for each object and specified pinch posture prior to data collection. The order of the objects being manipulated was randomized to minimize a potential training or order effect. The participant was instructed to move the object in concert with the moving cursor using only their fingers.

The path of object motion varied for each object. For the cork task, participants were instructed to rotate the cork in a clockwise motion away from the body to reach the peak of the sine wave. The valley corresponded to rotating the cork back in a counter clock-wise fashion towards the body. The wine task required that participants hold the stem of the glass and rotate forward (away from the body) to reach the peak and rotate backwards (towards the body) to reach the valley. For the pen task participants pushed the pen forward on the wheeled platform to attain the peak and then needed to pull the pen and the wheeled platform backwards in order to reach the valley. When evaluating the temporal accuracy and amplitude consistency, the peaks and valleys of the sine wave corresponded to these motions.

Synchronized data becomes important when comparing precision and accuracy of motion both in terms of amplitude, timing and overall cross-correlation. Therefore, the reference computer waveform and the miniBIRD performance trajectory were triggered to record simultaneously. The wrist electro-goniometer was collected separately and recording began prior to the trigger to capture the start position of the wrist. The wrist was not splinted to prevent movement as this could potentially affect the "natural performance" during manipulation of the object.

Normal manipulation required a two-finger pinch for the cork task (thumb and index) and three-finger pinch for the wine and pen task (thumb, index, and long). When collecting data on the simulated index finger amputation condition, two-finger pinch was performed with the thumb and long finger while, three-finger pinch required the thumb, long and ring finger. The simulated condition was used to test reproducibility of performance between time one and time two (test retest reliability) and to compare performance in the task protocol to the clinical dexterity test scores to determine if a relationship was present (concurrent validity). Using a simulated disability increased the difficulty for the manipulation task which then allowed several grades of accuracy scores across participants to be obtained. This provided more variable data to rank and correlate to the clinical tests. Normal manipulation of the objects was collected on time one only.

To assess the task protocol for test retest reliability participants returned one week later to complete the task protocol again (time two). During this session the remaining two clinical tests of fine motor dexterity; the O'Connor Tweezer Dexterity Test and the Nine Hole Peg Test were administered.

Data Analysis

The waveforms were analyzed using Matlab software Version 7 custom scripts. All data was filtered using a low-pass 4Hz filter which eliminated the high frequency noise without changing the waveform. The middle 9 cycles were selected for all objects and trials. The first 4 cycles and last 6 cycles were excluded. This was to ensure that participants were in sync with the task and ensure that fatigue was not likely to play a role. In order to ensure that complete cycles were included for the temporal and amplitude analysis the first and 9th cycle were excluded from analysis, leaving 7 cycles for the temporal and amplitude data analysis.

Cross-Correlation

A cross-correlation function of the middle 9 cycles of each trial was performed. The performance waveform was correlated to the reference waveform for each trial and the resultant r-value was used as the index of performance. Timing errors were evaluated separately and not taken into account in this cross-correlation analysis. To establish test retest reliability the r-value obtained from the simulated index amputation condition on time one was compared to time two. To evaluate changes in accuracy between normal and a simulated index amputation condition the r-value for normal manipulation was compared to the simulated amputation condition on time one. No outliers were identified. (n=20)

Clinical Test Scores

The r-value obtained by cross-correlation analysis on the simulated amputation condition on time one was ranked for each object and correlated with the rank score for each of the common clinical tests. Rank performance of each object manipulation and clinical test were compared to determine if there was a correlation or relationship to establish concurrent validity.

Temporal Accuracy

To evaluate accuracy in reaching the peaks and valleys of the sinusoid with respect to time, the differences in time (ms) from the performance peak to reference peak and performance valley to reference valley were calculated for the middle 7 cycles. The overall temporal difference independent of direction (lag or lead) obtained from the analysis was compared between time one and time two to establish reproducibility and consistency between sessions. Timing errors were also compared to evaluate changes in timing between the normal manipulation to the simulated index amputation condition. Within each object manipulation, outliers were identified as being 3SD above the mean and were excluded from the analysis (cork n=19, pen n=18, wine n=19).

Amplitude Consistency

To evaluate the consistency in the amount of object motion, the overall amplitude excursion for each cycle of the MiniBird (excursion of the peak and valley position) was computed. The same 7 cycles that were used for the temporal analysis were selected for amplitude analysis. The coefficient of variation was calculated from the 7 cycles for each trial by dividing the mean by the SD. The resultant variance was then used as a measure of amplitude consistency with which to compare changes between time one and time two and normal manipulation to the simulated index amputation condition. No outliers were identified (n=20).

Goniometer Data

The raw data signal was converted to degrees using the calibration formula (Biometrics, Gwent, UK). As the goniometer began recording approximately 2-3 seconds prior to the MiniBird and computer waveform, the mean of the first 10 data points collected were used to evaluate the start position of the wrist. The goniometer sampled at 100Hz and each trial lasted 45 seconds. Data points from 500-4500 were selected to ensure the entire trial was evaluated. The minimum and maximum value for each trial for both radial/ulnar deviation and wrist flexion/extension were subtracted to calculate the total motion for each trial.

Statistical Analysis

The Wilcoxon Signed Rank Test was used to evaluate changes in temporal, amplitude and cross-correlation data between both time one and time two as well as normal to simulated amputation conditions. Spearman's Rank correlation was used to rank the 'R' value obtained from the miniBIRD performance cross-correlation to scores obtained from the clinical tests.

Clinical Relevance

Confirming the reliability of the protocol as an objective tool to quantify movement accuracy sets the stage for future research to study patient populations with hand injuries. This protocol measures consistency and fluidity of object manipulation with respect to both amplitude and timing, reproducing typical functional requirements. Clinical tests of dexterity measure speed with accuracy based on time to complete the test. While quantifying a component of fine motor manipulation and confirming reliability of the task protocol was the aim of this research study, future research could quantify virtually any grasp or reach function with the potential to make this a universal tool to measure the hand and upper extremity, regardless of diagnosis. Since any object can be instrumented and the amplitude and frequency can be adjusted, the protocol can be altered to simulate any upper extremity task, thus making the evaluation system completely transferable as a functional measure.

Limitations and Assumptions

This protocol quantified a small sample of objects that would be manipulated in daily life. Either a two or three digit grasp was chosen to select and quantify fine motor skills. Quantification of accurate movement for other fine dexterous tasks was beyond the scope of the present study.

The aim of future research is to quantify the functional outcome pre and post secondary reconstructive procedures after hand trauma. Because of this, a simulated index amputation injury was chosen for the current study. The lack of individuated movement due to the structure and anatomy of the hand precludes the appropriate simulation of multiple digital loss. A simulated index finger amputation was chosen as it is a commonly injured finger and because of its relative anatomic independence in relation to other digits and importance in normal fine motor manipulation. The results will likely overestimate the degree of impairment as previous research has shown that rehabilitation and motor relearning results in little functional loss in motivated individuals.

There was the potential for an order effect in that the protocol was repeated to evaluate test retest reliability. The order effect is the change in behavior that may result from the sequence of activities presented and may reflect short term learning, fatigue or boredom. In an attempt to minimize the order effect, participants were tested one week apart and the order of the objects presented was randomized.

Manuscript 1

Objective Evaluation of Fine Motor Manipulation – A New Clinical Tool

Elizabeth R. Andersen Hammond, BMR-PT

School of Medical Rehabilitation, Faculty of Medicine

University of Manitoba

Keywords: Fine Motor Manipulation, Dexterity, Assessment, Motion, Hand

INTRODUCTION

In order to be evidence-based practitioners, therapists need to quantify hand function to plan treatment, evaluate the effectiveness of treatment, provide appropriate adaptive equipment, and outline job restrictions to third party payers and employers. To date, hand function has been measured using standardized timed tests and observational grading of tasks. These standardized timed tests are quick and easy to administer, and viewed as representing some general ability to perform functions relating to fine motor tasks (Kimmerle, 2003;Bear-Lehman J., 1989;Rice et al., 1998). Time to complete these tests imply a level of dexterity when compared to age matched norms. It has been recognized that "the resulting time scores do not describe the full repertoire of the hand to complete the necessary functions at work or in daily life and ignore challenging motor control and planning movements"(Kimmerle, 2003). While time is an important component in efficient object manipulation, these tests do not evaluate movement quality during manipulation of an object. In addition, the objects are limited to pegs or disks which represent only a small subset of geometric and material properties that are manipulated in daily life.

Research into the evaluation of human hand movement and functions has involved many disciplines including; psychology, neuroscience, physiology, biomechanics, robotics and rehabilitation. How the normal human hand grasps and manipulates objects by producing coordinated contact forces, between fingers and objects is only beginning to be understood. Evaluation of motor impairment and the ability to restore function of the hand and arm after cortical brain stem and spinal cord injuries has also provided insights into hand function (Carey et al., 2002;Memberg and Crago, 1997;Yamanaka et al., 2005), but little attention has been given to quantification of accuracy and precision of object manipulations after a musculoskeletal hand injury.

A variety of methods and instruments have been used to quantify hand and finger function including motion analysis, electro-goniometers with visual tracking targets, magnetic motion sensors, instrumented gloves with force sensors and goniometers, and instrumented objects with force strain gauges (Carey et al., 2002;Degeorges et al., 2005;Dipietro, 2003;Flanagan et al., 1999;Mason et al., 2001;Memberg and Crago, 1997;Santello et al., 2002;Yang et al., 2002). Miniaturized position and motion tracking sensors can be used for sensing the three dimensional position of an object over a discrete visual tracking system. Electro-magnetic sensors have been used in hand motion studies to track the three-dimensional position of the wrist during reach (Baud-Bovy and Soechting, 2001; Santello et al., 2002).

Studies have evaluated different components of hand function including: the influence of feed forward sensory guidance in pre-shaping the hand prior to grasping objects (Santello et al., 2002); the ability of the hand to coordinate movement patterns of the digits in response to auditory stimuli (Balasubramaniam et al., 2004); hand synergies in reaching and precision grip (Mason et al., 2001); kinematic studies measuring rotations of the digits in flexion (Degeorges et al., 2005); the ability to use a neuroprosthetic device after spinal cord injury (Memberg and Crago, 1997); and, fMRI studies to understand the dynamic neural system of hand function post-stroke (Carey et al., 2002; Talati et al., 2005). All of these studies are directed towards understanding the complex interactions between vision, touch, memory, the CNS, forces, synergies, and the biomechanics and anatomy that enable the hand to grasp and manipulate objects.

When quantifying object handling or manipulation tasks, studies have used computer-generated targets including sine waves or figure of eight tracking tasks (Carey et al., 2002;Yamanaka et al., 2005). Sine waves are cyclical movements, symmetric in position and velocity ideal for evaluation of continuous movement tasks (Balasubramaniam et al., 2004). Auditory signals such as a metronome have also been used instead of visual tracking to initiate and time synchronicity of movement. When quantifying motor control and movement accuracy, "control of timed repetitive actions, whether the cues are internal, auditory or visual must satisfy two goals, precision and accuracy in timing and organization of movement parameters to meet interval requirements" (Balasubramaniam et al., 2004).

A need for developing an accurate assessment tool to measure hand function has been identified in the rehabilitation literature (Kimmerle, 2003;Bear-Lehman J., 1989). The current clinical tests are limited in that they offer only a gross estimate of fine motor function. The scientific literature have used electro-magnetic sensors and electro-goniometers (Santello et al., 2002;Carey et al., 2002) and visual tracking with a sine wave (Carey et al., 2002) to assess and grade performance of the normal and neurologically impaired hand. The current study expands on these previous studies by using these tools to quantitatively evaluate a component of fine motor hand function after musculoskeletal injury (a simulated index finger amputation condition).

As hand therapists, it is important to be able to objectively grade the performance of the individual in fine motor manipulation of the hand. Objective evaluation of performance as an outcome measure is important for assessment, treatment, and evidence-based practice. At present, a reliable tool that can measure accuracy, consistency and precision in movement with fine motor tasks is not available.

The purpose of this study was to determine the reliability and validity of a new tool which could assess motor performance independent of the objects being used. For clinical comparison, performance with this tool was compared to four commonly used clinical tests of fine motor dexterity: the Purdue Pegboard, Minnesota Rate of Manipulation, Nine Hole Peg Test, and the O'Connor Tweezer Dexterity Test. It was hypothesized that the task protocol would be a reliable method to evaluate movement accuracy related to amplitude and temporal dimensions. It was further hypothesized that the clinical tests scores would correlate to the task protocol and establish concurrent validity.

METHODS AND MATERIALS

Subjects

Twenty right handed participants (ten males; ten females; mean age 34; range 24-47 years) were recruited from students and staff at the University of Manitoba and Health Sciences Centre via advertisement. Participants were excluded if there was past history of upper extremity pathology with residual deficits, recent injury to the right arm, cognitive impairment or any history of neurological impairment affecting balance, vision or coordination. A screening assessment ensured that each participant had full range of motion of the hand, normal sensibility (using a 2.83 monofilament from the Semmes

Weinstein Monofilament Test) and normal visual acuity (tested with eye chart for 20/20) to complete the computer tracking task . In addition, volumeter measurements were taken to measure hand size of each participant. Volumeter measurements record the amount of water displaced when participants submerge their hand in water and provides a gross measure of hand size/volume. Participants were fully informed about the procedure and consent was obtained prior to participation. This study was approved by the University of Manitoba Health Research Ethics Board.

Instrumentation

A computer generated sinusoidal trajectory showing a bright red dot on the computer monitor provided the visual open-loop tracking task. The amplitude and frequency of the cursor movement was adjusted to match the natural amplitude and speed of movement for manipulation of the objects selected. Preliminary tests showed that ten percent of the height of the computer screen at a frequency of 0.4 Hz felt the most comfortable for participants. These parameters were then selected with a forty-five second duration producing 19 cycles for analysis. The object properties that were considered included geometric size and shape, texture and friction. The size and weight of the object was chosen to reflect typical objects that would normally be manipulated with two or three fingers. Thus, the accuracy of performing tasks requiring various degrees of precision, requiring different movement strategies and sensori-motor demands with a variety of pinch postures were measured.

The three objects selected for manipulation are as follows:

1. A cork for rotation mimicking any small dial (two-digit manipulation)

2. A pen that pushes a small wheeled platform forward and back mimicking writing or pushing food on a plate (three-digit manipulation)
3. A plastic wine glass rotating the stem of the glass forward and backward (three-digit manipulation)

A simulated index-finger amputation condition was chosen for this study. In this simulated condition, all two-finger manipulations occurred with the thumb and long finger and all three-finger manipulations occurred with the thumb, long and ring fingers. Participants moved the object following a linear or angular plane of motion depending on the object being manipulated. Objects were instrumented with the miniBIRD Model 800 DC magnetic tracker (Ascension Technology, Burlington,VT, USA). The miniBIRD accurately measures the real-time, instantaneous position and orientation of the sensor with six degrees of freedom at 120Hz. Thus, the miniBIRD can sense linear and angular movements in three dimensional space (x,y,z). The SG65 Biometrics electro-goniometer (Biometrics, Gwent, UK) was used to record the wrist range of motion at 100 Hz. The goniometer was attached dorsally along the third metacarpal and distal forearm with double-sided adhesive tape. The clinical tests used included the Purdue Pegboard Model 32020 (Lafayette Instrument Company), the 1969 edition of The Minnesota Rate of Manipulation, placing and turning sub-sets (Western Psychological Services), the O'Connor Tweezer Dexterity Test Model 32022 (Lafayette Instrument Company) and the Nine Hole Peg Test (Northcoast version).

Task Protocol

Following the screening assessment, two clinical tests were administered to participants excluding the index finger to simulate an amputation. Four trials of The Minnesota Rate of Manipulation 'Placing Test' and three trials of the 'Right Hand Test' for the Purdue Pegboard were collected.

After performing the clinical tests, participants were comfortably seated in front of a computer screen. Specific shoulder and elbow postures were not controlled to ensure that manipulation of the objects was performed as naturally as possible. All participants were instructed that object manipulation was to occur using only the fingers and not wrist motion. Participants were allowed one practice trial to adopt a comfortable start posture, ensure a stationary wrist throughout the trials and exclude the index finger from the task. The order of the objects being manipulated was randomized to minimize a potential training or order effect. The participant was instructed to move the object in concert with the moving cursor.

The path of object motion selected for each object varied. For the cork task, participants were instructed to hold the cork horizontally between the thumb and long finger and rotate the cork in a clockwise motion (away from the body) to reach the peak and counter-clockwise (towards the body) to reach the valley of the sine wave. The wine task required that participants hold the stem of the glass between the thumb, long and ring fingers and tilt the glass forward (away from the body) to reach the peak and tilt backwards (towards the body) to reach the valley. For the pen task participants pushed the pen forward on the wheeled platform to attain the peak and then pulled the pen and the wheeled platform backwards to reach the valley holding the pen between the thumb, long and ring fingers. When evaluating the temporal accuracy and amplitude consistency, the peaks and valleys correspond to these specific motions for each object.

Each object was instrumented with the miniBIRD motion sensor at a marked location. The magnet was kept stationary throughout the data collection process, subjects were seated in the same position and the object with the sensor was positioned each time to ensure the direction of motion was consistent across subjects and trials.

A custom trigger was used to begin recording (synchronize) motion data of the moving on screen cursor (visual target) and the miniBIRD motion sensor. The electro-goniometer was controlled separately and data acquisition started prior to the trigger. One week later participants returned to complete the protocol again (time two). This was to assess for reliability of the task protocol. During this second session the remaining two clinical tests of fine motor dexterity; the O'Connor Tweezer Dexterity Test and the Nine Hole Peg Test were administered.

Data Analysis

The middle 9 cycles of the 19 collected for each trial were chosen for data analysis and filtered with a 4 Hz low-pass filter. The data from each trial was processed using custom scripts in Matlab version 7.1 and then exported for offline analysis. Of the 19 cycles collected the first 4 cycles were excluded to ensure participants were insync with the reference trajectory. The last 6 cycles were also excluded to limit the potential for fatigue to interfere. Nine cycles were then included in the cross-correlation analysis. To ensure that complete cycles were compared for all participants, for both the temporal accuracy and amplitude consistency the first and last cycles of the selected 9 were excluded, leaving 7 cycles included for analysis.

A cross-correlation was performed to compare the reference to performance waveform for each trial. The resultant r-value was used as an index of global performance to compare time one with time two to establish test retest reliability. R-values on time one were used to compare the task protocol to the standardized clinical dexterity test scores and establish concurrent validity.

Temporal accuracy was analyzed by calculating the mean phase differences in milliseconds between the peaks and the valleys of the reference and performance waveforms for the 7 cycles of each trial.

Amplitude consistency, expressed as the coefficient of variation, was analyzed by comparing the variability (excursion of movement between peak to valley) between each cycle.

Raw data collected by the goniometer data was converted to degrees using the conversion formula (Biometrics, Gwent, UK). The total wrist motion for each trial (all 9 cycles) was calculated by subtracting the maximum value from the minimum value for both radial/ulnar deviation and flexion/extension. The mean value of the first 10 data points was used to determine the start position for flexion/extension and radial/ulnar deviation.

Wilcoxon Signed Rank Test was used to establish if statistically significant differences were found between time one and time two for the cross-correlation, temporal, and amplitude data. Spearman Rank Correlation was used to identify relationships between performance of the task protocol and the standardized tests of dexterity. Statistical significance was determined at $p<0.05$ level.

RESULTS

Results are described as the group mean value ± the standard error (SEM) unless specifically stated otherwise.

Participants

Males and females were compared with respect to age, hand size and performance in the task protocol and clinical tests of dexterity. There was no difference in ages (females 33.5±7.7, males 35.1±7.1 years). As expected, males had larger hand volumes compared to females (523±63 vs 388±27 ml), $p<0.001$. Figure 1 clearly shows the hand volume differences relating to hand size. With respect to the cross-correlation, males performed better (median r-value 0.957) on the cork task compared to females (median r-value 0.900) $p<0.001$. No other differences between genders were identified.

Cross-Correlation

Cross-correlation is a technique which can be used to compare two waveforms. R-values range from -1 (waveforms are completely opposite) to +1 (waveforms overlap perfectly). The resultant r-value (reference and performance comparison for each trial) was used as the index of performance. The index of performance (r-value) on time one was compared to time two using the Wilcoxon Signed Rank Test. Figure 2 illustrates the reproducibility in object performance for each of the objects manipulated. Performance on time one (black circles) is not significantly different from performance on time 2 (open circles), clearly indicating that participants were able to follow the waveform consistently. This confirms that participants moved in a similar pattern on both times, establishing reproducibility of the task protocol.

Concurrent Validity

Performance for all three object manipulations (using the r-value from the cross-correlation) and clinical test scores were ranked. If the task protocol and standardized tests both measure the same aspects of hand function a positive correlation would be expected. Contrary to the hypotheses, no positive correlations were identified between the object manipulations and the clinical test scores as the scattergrams in Figure 3 clearly demonstrate. In addition to this lack of relationship, Figure 3A shows a moderate negative correlation (-0.584) between the cork task and the Nine Hole Peg Test (NHPT). This indicates that a higher r-value (better performance) on the cork task relates to increased time to complete (poorer performance) on the NHPT.

Table 1 summarizes the correlation coefficients between each of the clinical dexterity tests. Moderate positive correlations were found between the dexterity tests, specifically, the NHPT and Purdue (R= 0.557), and the NHPT and MRMT (R= 0.508) indicating that these tests measure similar aspects of hand function. Although the NHPT related well to the other dexterity tests it was found be either unrelated or negatively related to the task protocol. Thus, it appears that different aspects of hand function are being measured with the task protocol compared to the clinical tests of dexterity.

Temporal Accuracy

Temporal accuracy was assessed by computing the time (phase) difference between the reference and performance waveforms in reaching the peaks and valleys of the sinusoidal curve. Figure 4A shows a graphical representation of the time differences in peaks and valleys that were computed for one cycle. For each trial there were seven peak time differences and seven valley time differences. The peak time (mean ± SEM) and the valley time (mean ± SEM) were calculated for each trial and object. When the peak and valley time differences were compared, the Pen task showed that the peaks were consistently more in phase with the reference than the valleys (time 1, $p<0.04$ and time 2, $p<0.02$). No other differences were found between the peaks and valleys. Figure 4B clearly shows reproducibility in task performance with respect to time. Timing differences in reaching the peaks and valleys were compared between time one and time two for the population (cork n=19, pen n=18, wine n=19). Outliers were defined as 3SD above the mean and were removed from the temporal analysis. There were no significant differences between any of the objects, establishing consistency within the temporal domain. This indicates that participants were consistent in timing their manipulation of the objects to follow the trajectory of the cursor.

Amplitude Consistency

Amplitude consistency was assessed by computing the excursion between the performance peak to valley of the sinusoidal curve for each cycle. Seven cycles were analyzed for each trial. Figure 5A illustrates a graphical representation of the amplitude excursion that was computed for one cycle. The mean of the seven cycles was divided by the SD to obtain the coefficient of variation. The coefficient of variation (CV) is a measure of the variability within each trial. The CV on time one was compared to time two. Statistically no differences were found. Figure 5B clearly shows that participants consistently reproduced the same excursion per cycle across the 7 cycles on two separate times for all objects.

Wrist Motion

The start position varied between each object, but was consistent from time one to time two (Figure 6). Wrist movement during object manipulation was recorded and the mean excursion in degrees from the start position is summarized in Table 2. Figure 7 shows the range of wrist motion for all participants and all objects during the trials. Although wrist motion occurred, it was minimal and consistent between time one and time two (NS).

DISCUSSION

Quantifying hand function is complicated and our current assessment techniques to measure function do not provide a complete picture. According to the American Society of Hand Therapy (ASHT) guidelines and many other authors, the current tests of hand function are inadequate and perhaps invalid (Kimmerle, 2003;Nicolson, 1992;Bear-Lehman J., 1989;Rudman, 1998). The present study begins to address this longstanding problem by developing a functional framework to quantify and objectively evaluate performance in fine motor object manipulation with the hand.

Aside from hand volume, there were minimal gender differences identified. The overall cross-correlation in manipulating the cork was the only task that was statistically different between males and females, with males producing more accurate results. This may in part be due to the small number of participants in this study and with greater numbers these differences could become negligible. A second explanation may be that manipulation of the three objects selected were not tasks that differentiate performance between males and females, and that with further research, gender differences might be found.

The r-values obtained from the cross-correlation on time one when compared to time two, produced similar results making the task protocol reproducible. The same was true for the amplitude analysis with the amount of excursion per cycle demonstrating similar results on both times. Temporal analysis was also consistent, producing similar results when the phase shifts between performance and reference waveforms were compared between the two sessions. Interestingly, there were differences when the phase difference was compared between the peaks and the valleys during the pen task. Participants were consistently more in phase with peaks than the valleys for the pen task. This may be explained by the increased difficulty on the return phase of the task. Moving a pen on an unstable platform requires more sensori-motor control demands and constant sensory feed forward adjustments to properly control the motion. The difficulty increased further when pulling the pen back on the return phase as participants now needed to overcome friction and drag to reach the valley. This would be consistent with the decreased temporal accuracy on the return phase. Generally, with this task protocol, absolute temporal accuracy, amplitude consistency, and overall global performance can be calculated easily to obtain performance scores. This task protocol proved to be a reliable tool in that the three objects investigated thus far demonstrated test retest reliability.

The task protocol when compared to the current standardized tests of dexterity showed either a lack of relationship or a negative relationship. Clearly, different aspects of hand function were being measured. The current clinical tests of dexterity measure speed of completion and are limited to simple grasp and transport of pegs which is indirectly associated with precision/accuracy. The task protocol directly measures temporal accuracy and consistency of movement. Unlike the timed dexterity tests this protocol is not limited to pegs or discs but incorporates actual objects used in activities of daily living. As this protocol does not depend on speed of completion to grade performance, any frequency and amplitude can be chosen to reflect actual requirements for manipulation. Further, any number of objects of varying sizes, shapes and textures can be instrumented to evaluate specific hand function requirements. Although the current study used a simulated finger amputation, this tool has the potential to be a universal method to evaluate and treat the hand and upper extremity, regardless of the diagnosis.

In conclusion, the present study has demonstrated that fine motor manipulation can be quantified with respect to amplitude and timing using actual objects, a motion sensor and a computer generated visual tracking target. This new tool has been shown to be a valid and reliable method of objectively evaluating a component of fine motor hand function in the manipulation of three objects in participants with a simulated index finger amputation. Future studies are planned to include a larger number of participants and a range of objects to further develop a functional framework. The goal is to have a subset of objects of varying size, shape and textures that reflect large portion of the manipulation requirements that are involved in daily life. Our goal is to eventually apply this functional framework to the patient population which will provide a valid, reliable and objective outcome measure that is required in therapy for treatment, assessment and research directed at evidence-based practice.

Figure 1. Hand Volumeter Measurements

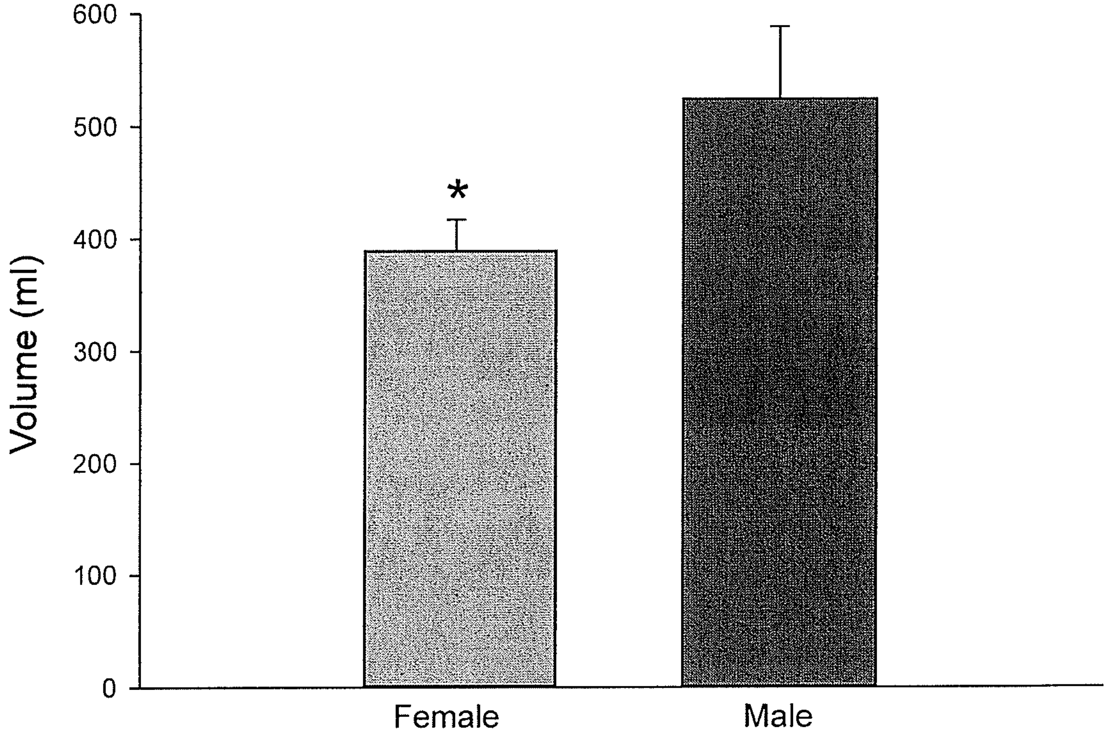


Figure 2. Reproducibility of Object Performance

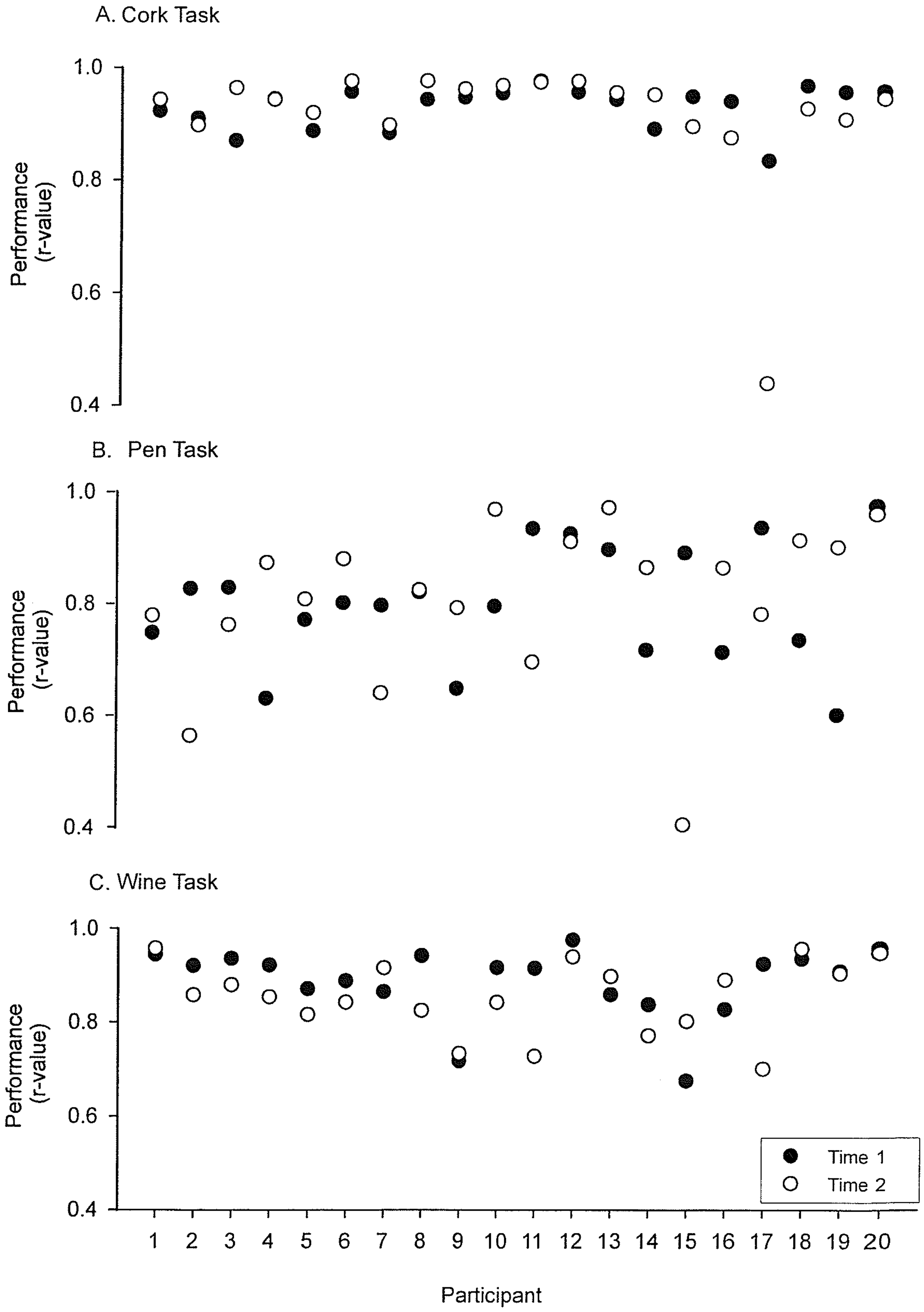


Figure 3. Correlation Between the Task Protocol and Common Clinical Tests of Dexterity

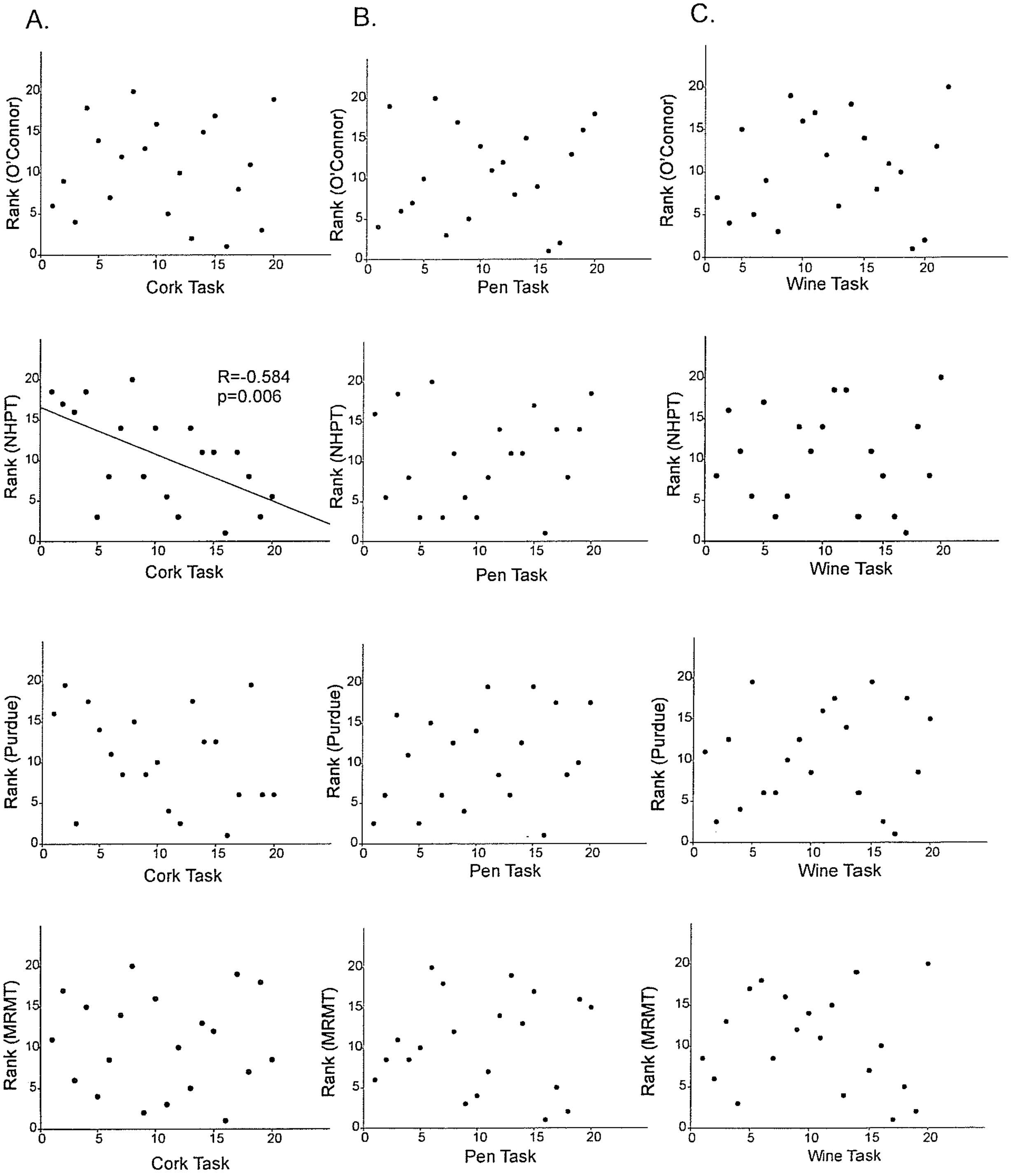


Figure 4. Reproducibility of Temporal Accuracy

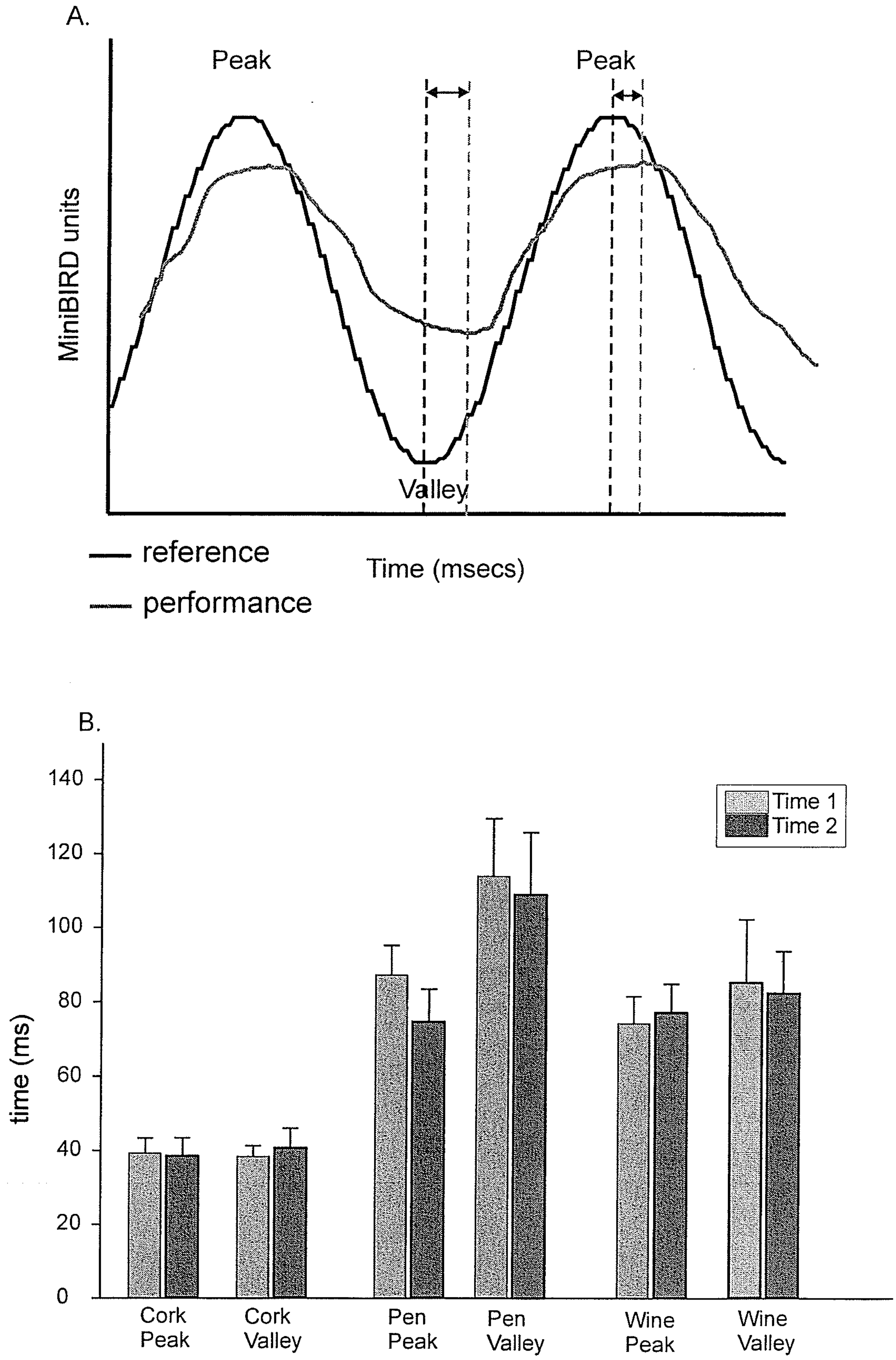


Figure 5. Reproducibility of Amplitude Excursion

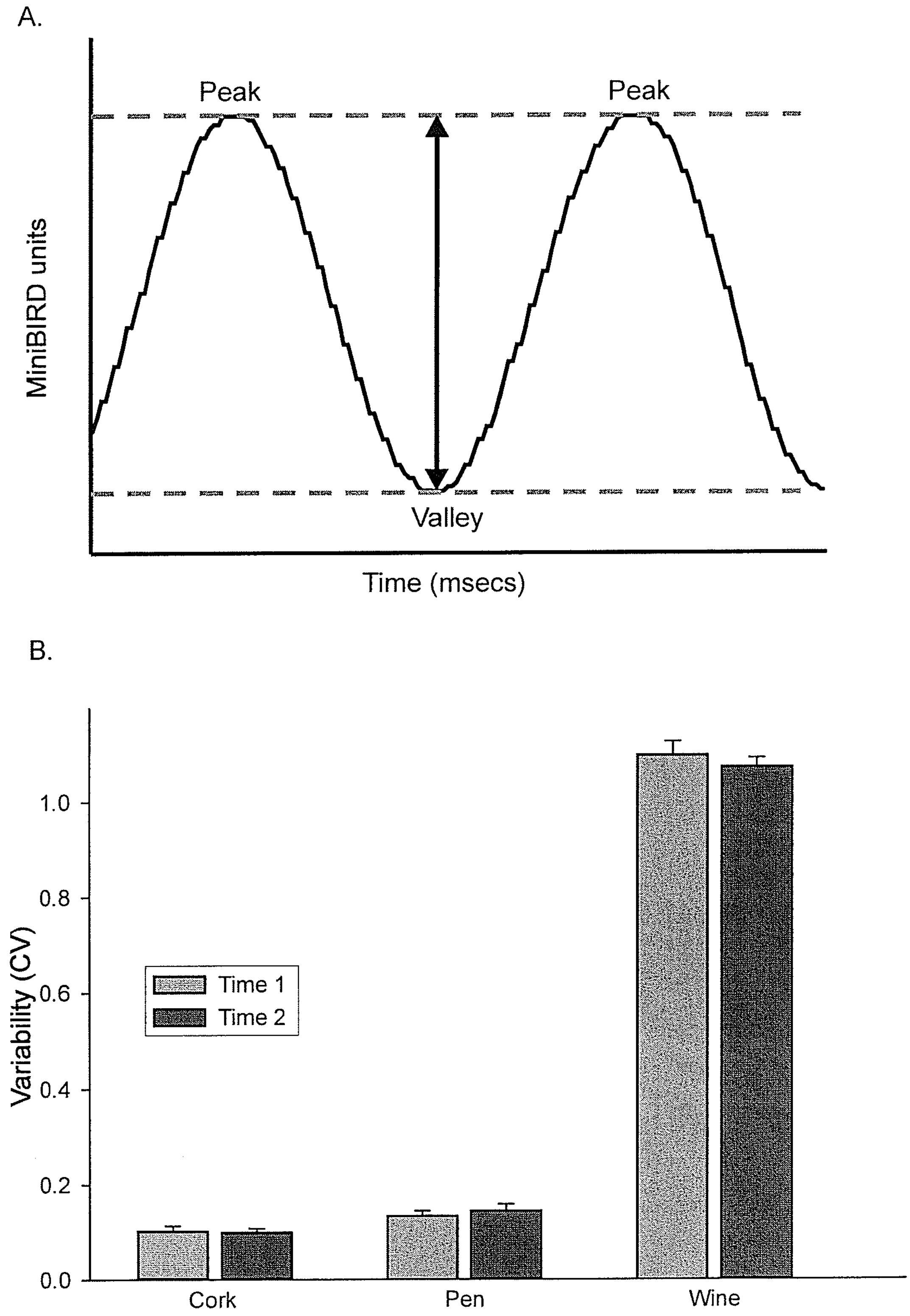


Figure 6. Wrist Start Position

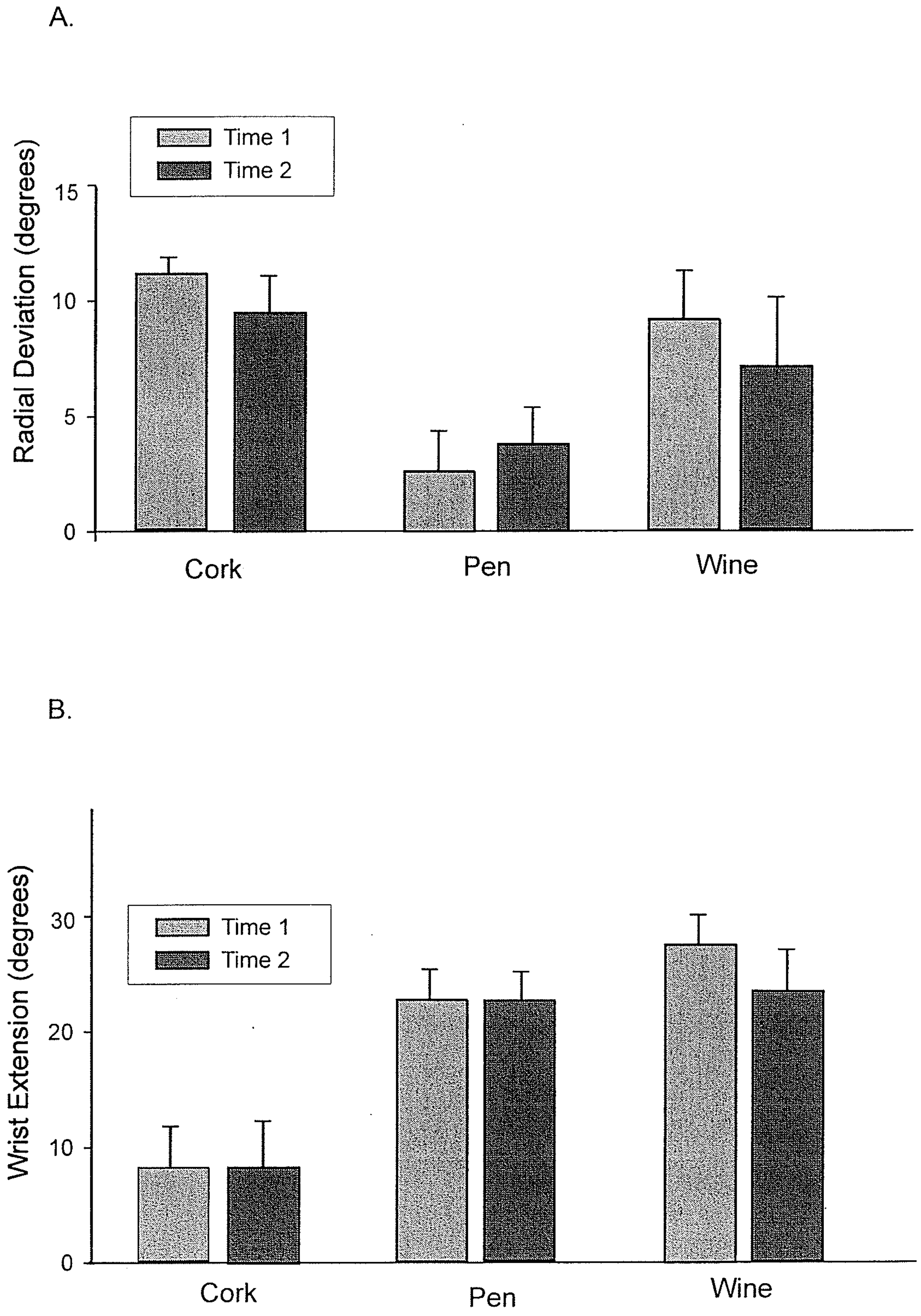


Figure 7. Wrist Motion During Object Manipulation

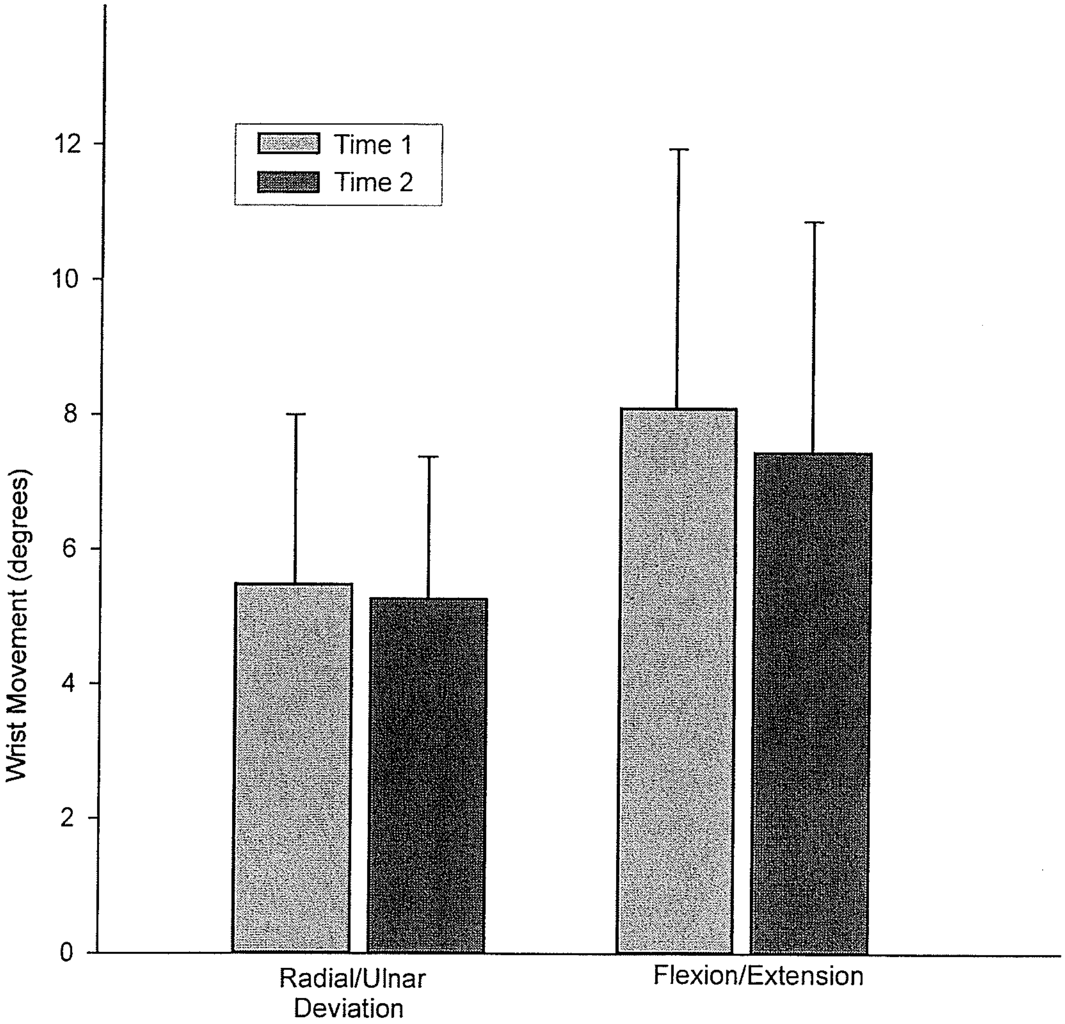


FIGURE LEGENDS

Figure 1. Hand Volumeter Measurements

This graph shows the mean ± SEM of the hand volumes of the males (n=10) and females (n=10). Volume in milliliters is along the y-axis. Males had significantly larger hands (523±63ml) than the females (388±27 ml), (t-test; $p<0.001$).

Figure 2. Reproducibility of Object Performance

These graphs compare performance of each task to the reference waveform. R-values obtained from the cross-correlation between performance and reference waveforms are used as an index of accuracy and are on the y-axis. The x-axis is each participant (n=20). Closed circles represent the performance score on Time 1 and open circles represent performance scores one week later (Time 2). Figure 2A is performance on the cork task, Figure 2B is performance on the pen task and Figure 2C is performance on the wine task. There are no significant differences in participant performance between the two times indicating reproducibility of object manipulation (Wilcoxon signed rank test; NS).

Figure 3. Correlation Between the Task Protocol and Common Clinical Tests of Dexterity

These plots compare performance of each task to four clinical tests commonly used to assess dexterity. Index of performance (r-values) for each object were ranked and plotted against ranked performance on the clinical dexterity tests. Performance on the dexterity tests is located along the y-axis and performance of each object task is shown along the x-axis for all 20 participants. Figure 3A is the scattergram comparison of the cork task. Performance on the nine hole peg test had a moderate negative correlation to performance on the cork task, indicating that as accuracy increased for one task it diminished in the other (R = -0.584). Figures 3B and 3C illustrates the relationship of the pen task and wine task performance to the clinical tests of dexterity respectively. There were no positive correlations between performance of the tasks and the clinical tests of dexterity (Spearman Rank Correlation).The lack of relationship between the timed clinical tests of dexterity and the task protocol suggests that these tests are measuring different aspects of hand function.

***Figure* 4. Reproducibility of Temporal Accuracy**

This graph demonstrates the temporal phase shift in object performance for participants. Figure 4A shows a representative waveform comparing the trajectory of performance for one of the tasks to the trajectory of the reference sinusoidal waveform. Along the y-axis is the amplitude excursion, while the x-axis is time. The arrows illustrate the differences in time between the peaks and valleys of the reference to performance sinusoidal waveform that were calculated for each trial.

Figure 4B compares the temporal phase shift between the reference and performance waveforms on two testing days. Values indicate temporal accuracy of participants (cork n=19, pen n=18, wine n=19). Phase shifts for peaks and valleys are compared between Time 1 and one week later (Time 2). Time (ms) is shown on the y-axis. Peaks and valleys relating to each object are indicated on the x-axis. Values are expressed as mean ± SEM for all participants over 7 cycles. There are no significant differences in temporal performance between the two times for any of the tasks indicating that participants timing was consistent (Wilcoxon signed rank test; NS).

Figure 5. Reproducibility of Amplitude Excursion

Figure 5A illustrates the calculation performed to obtain the excursion of motion. The peak subtracted by the valley as indicated by the arrow outlines the excursion for one cycle. Figure 5B illustrates the relative amplitude excursion in object performance for all participants on Time 1 and Time 2 (n=20). The Coefficient of Variation (CV) is used as a measure of variability. The CV expressed as the mean ± SEM is calculated for all participants and is located along the y-axis. Objects are shown along the x-axis. There are no significant differences in performance with respect to amplitude excursion between Time 1 and Time 2 indicating that the amplitude excursion remained consistent and participants manipulated the objects in a similar manner at both times (Wilcoxon signed rank test; NS).

Figure 6. Wrist Start Position

All the participants selected a starting wrist position of radial deviation and wrist extension. This graph shows the start positions that participants chose for each task during Time 1 (light grey bars) and one week later at Time 2 (dark grey bars). Figure 6A illustrates the start position with respect to radial deviation. Degrees are shown along the y-axis and objects are on the x-axis. Values are mean ± SEM for all participants. Similarly, Figure 6B shows mean wrist extension in degrees (y-axis) and objects along the x-axis. Results demonstrate that participants chose a consistent start position on both time 1 and time 2 (Wilcoxon signed rank test; NS).

Figure 7. **Wrist Motion During Object Manipulation**

This graph compares wrist movement between Time 1 and one week later (Time 2) for all participants (n=20) during manipulation of all objects. A composite score was obtained by averaging the mean movement for both radial/ulnar deviation and wrist flexion/extension for all participants and the three objects tested from their chosen start position. The x-axis shows the plane of wrist motion; Time 1 is shown in light grey bars, Time 2 is shown in dark grey bars. Values are mean ± SD for all participants. The y-axis is degrees of movement (deviation time one: time two is 5.48±0.34: 5.26±0.34, flexion/extension time one: time two is 8.09±0.58: 7.44±0.48). Although wrist motion occurred, it was consistent between Time 1 and Time 2 (Wilcoxon signed rank test; NS).

TABLES

Table 1 summarizes the correlation coefficients of all the clinical dexterity tests and the task protocol.

Table **1. Correlation Coefficients**

	Purdue	NHPT	MRMT	Cork	Pen	Wine
O'Connor	0.321	0.269	0.366	-0.0165	0.0857	0.110
Purdue	------	0.557*	0.261	-0.332	0.287	0.144
NHPT	------	------	0.508*	-0.584*	0.114	-0.0151
MRMT	------	------	-------	-0.0271	0.0211	-0.114

* Statistically Significant $p<0.05$

Table 2 compares the mean wrist deviation and flexion/extension for all participants for each object during Time 1 and Time 2 (NS). Values are in degrees (mean ± SD).

Table **2. Wrist Motion**

Task	Cork		Pen		Wine	
Motion (Degrees)	Deviation	Extension	Deviation	Extension	Deviation	Extension
Time one	6.059± 2.535	9.689± 5.102	4.075± 1.768	7.317± 3.820	6.293± 2.881	7.281± 4.323
Time two	5.269± 2.184	8.698± 4.783	4.293± 1.630	7.785± 3.274	6.214± 3.510	5.839± 2.375

Manuscript 2

A Comparison between Normal and a Simulated Index Finger Amputation in the Manipulation of Objects

Elizabeth R. Andersen Hammond BMR-PT
School of Medical Rehabilitation, Faculty of Medicine
University of Manitoba

Keywords: Accuracy, Motion Analysis, Simulated Amputation, Hand

INTRODUCTION

The functional importance of the hand seems obvious when one thinks of daily activities such as dressing, grooming, eating, handling objects, playing musical instruments, or fulfilling virtually any job demand. Tubiana identifies the most crucial functions of the hand being the sensory functions of touch and prehension (Tubiana, 1984). Prehension consists of several phases: approach, grip and release. Approach involves the trajectory of the hand towards an object and can be accomplished by vision, palpation, or memory. Grip consists of opening the hand, closing the hand around the object and regulating force. Release requires simultaneous action of intrinsics and long extensor muscles (Tubiana, 1984). These prehension stages are involved in all types of hand postures including those commonly adopted for tasks involving fine motor manipulation. Fine motor manipulation usually involves the thumb, index and long finger for various pinch postures including precision pinch, oppositional pinch, key pinch, and tripod pinch.

Attempts have been made to grade the functional importance of each digit and outline the basic requirements needed for a functional hand after a traumatic hand injury (Cheng et al., 2004;Jones et al., 1982;Soucacos, 2001;Soucacos et al., 1994). The basic requirement after a mutilating hand injury is to have a stable wrist and at least two fingers that can oppose each other. In order to provide superior function over a prosthesis, these fingers must be sensate and pain free (Moran and Berger, 2003).

The thumb is of primary importance as it functions in all types of grasp (Bueno, Jr. and Neumeister, 2003;Moran and Berger, 2003;Tubiana, 1984). The thumb has the ability to oppose all digits and the palm, and its strength and mobility make up 40% of hand function in an uninjured hand (Moran and Berger, 2003). This can increase to account for greater than 50% of hand function after mutilating hand trauma (Moran and Berger, 2003).

In the uninjured hand, it is thought that the index finger ranks second in importance due to its strength, ability to abduct, relative independence compared to the other digits and its proximity to the thumb (Moran and Berger, 2003;Tubiana, 1984). Despite its importance, the index finger is seldom replaced after finger amputation. The long finger compensates and replaces the index finger in precision pinch with minimal loss in hand function (Moran and Berger, 2003;Zachary and Peimer, 1997). The long finger has the most strength of the fingers in flexion and its central position allows for function in both precision and power grasps (Moran and Berger, 2003).

Hands and fingers are the most commonly injured body parts comprising 22% of all work injury related claims (Workers Compensation Board of Manitoba and Manitoba Labour and Immigration, 2005). In Manitoba, from 2000 to May 2007, 46.6 million dollars has been paid for time loss alone resulting from finger and hand injuries. Traumatic hand injuries including digital amputations are unfortunate work accidents that are all too common in the manufacturing, trades and service areas. These areas accounted for 72% of all hand injury claims from a total of 25,799 hand and finger claims (unpublished statistics provided by the Workers Compensation Board of Manitoba, May 2007).

In order to study and evaluate functional loss, hand injuries have been simulated in normal participants (Pennathur, 1999;Rondinelli et al., 1997). One study immobilized the 1st carpal meta carpal (CMC) of the dominant hand with a splint. In order to fully immobilize the CMC it was necessary to partially immobilize the 1st meta carpal phalangeal joint, wrist, and forearm. The American Medical Association (AMA) Guidelines rate this injury as moderate impairment. Results showed that despite a moderate impairment rating, participants were able to overcome loss of strength and range of motion to perform most complex functional tasks within the normal/low normal range. They concluded that "impairment rating is a poor estimator of functional loss in the hand" (Rondinelli et al., 1997).

Another study simulated finger amputation injuries and evaluated performance on numerous standardized tests including dexterity and lifting tasks. The simulated injury was extreme, all four fingers on the dominant hand and the thumb in the non-dominant hand. Not surprisingly, participants with the simulated injury had decreased functional capabilities (Pennathur, 1999). Simulating injuries in research can be helpful as the same impairments can be applied to all participants without other extraneous variables confounding results. However, caution must be taken when drawing conclusions as the hand operates as one functional unit and the ability to retrain the hand after injury is a variable that can impact overall results.

Grasping, transporting and manipulating objects with the fingers and hand are complicated interactions which have attracted considerable scientific attention (Carey et al., 2002;Dipietro, 2003;Flanagan et al., 1999;Mason et al., 2001;Pataky et al., 2004;Talati et al., 2005;Zatsiorsky et al., 2003). Studies have used a variety of technologies to quantify motion and forces including an electro-goniometer attached to the finger to record accuracy in tracking a computer sine wave (Carey et al., 2002), instrumented gloves that measure joint finger motion (Dipietro, 2003), 3D digital motion analysis systems (Mason et al., 2001), and instrumented objects with pressure sensors (Zatsiorsky et al., 2005). These studies provide methods to evaluate finger/hand function and have explored the relationships between movement, vision, sensation, memory, forces, synergies, and the biomechanics and anatomy that enable the hand to grasp.

Visual tracking using a sine wave with electro-goniometers (Carey et al., 2002) and motion analysis (Santello et al., 2002) have been used effectively to grade hand performance. Due to the importance of the index finger in fine motor manipulation and the current support in the literature that the long finger can compensate with little functional loss, the purpose of the present study was to evaluate changes in temporal and amplitude movement accuracy with tasks requiring fine motor manipulation between normal conditions and a simulated index finger amputation condition.

METHODS AND MATERIALS

Participants

Twenty right handed participants were recruited (ten males; ten females; mean age 34; range 24-47 years) An initial assessment confirmed that all participants had full range of motion of the hand, normal sensibility (using the 2.83 monofilament from the Semmes Weinstein Monofilament Test) and normal visual acuity (tested with eye chart for 20/20). Volumeter measurements were taken to measure hand size. Volumeter measures the amount of water that is displaced when the hand is submerged in a container and thus provides an indication of hand size. Demographic information was collected including date of birth, full name, and contact number. Participants were excluded if they had a past history of upper extremity pathology with ongoing functional deficits, recent injury to the right arm, cognitive impairment and neurological impairment (affecting balance, vision or coordination). The purpose and procedures were explained to participants and consent was obtained prior to participation. There was one experimental group that was exposed to both the normal and simulated amputation conditions on a single test day. This study was approved by the Health Research Ethics Board (HREB).

Instrumentation

A computer generated sine wave provided the visual open-loop tracking task. A bright red dot was displayed on the computer monitor producing a sinusoidal trajectory of movement. The participant moved the object in concert with the moving cursor following either a linear or angular plane of motion. The amplitude and frequency of the cursor movement was adjusted to match the natural amplitude and speed of movement (0.4 Hz). Nineteen cycles were collected.

Three objects were selected for manipulation. A cork for two-finger rotation mimicking any small dial, a pen that pushed a small wheeled platform forward and back mimicking writing or pushing food on a plate (three-digit manipulation) and a plastic wine glass tilting the stem of the glass forward and backward (three-digit manipulation). The size, weight, texture and friction of the objects reflect typical objects that would normally be manipulated with two or three fingers. Thus, movement accuracy was measured during tasks requiring various degrees of precision, different movement strategies and a variety of pinch postures. Normal two-digit manipulation required the thumb and index finger, while three-digit manipulation required the thumb, index and long fingers. During the simulated index finger amputation, all two-finger manipulations occurred with the thumb and long finger and all three-finger manipulations occurred with the thumb, long and ring fingers.

The miniBIRD Model 800 DC magnetic tracker (Ascension Technology, Burlington,VT, USA) was used to record movement during object manipulation. The miniBIRD motion sensor measures real-time position and orientation with six degrees of freedom. It senses linear and angular movements in three dimensional space (x,y,z) at 120 Hz. Each object was instrumented with the miniBIRD at a marked location. The magnet was kept stationary throughout the data collection process, subjects were seated in the same position and the object with the sensor was positioned each time which ensured consistency across subjects and trials.

The SG65 Biometrics electro-goniometer (Biometrics, Gwent, UK) recorded the range of motion at the wrist at 100Hz. The goniometer was attached dorsally to the back of the third metacarpal and distal forearm with double-sided adhesive tape. The wrist was not splinted to allow for natural performance and a self-selected start position by each participant.

Procedure

Following the screening assessment, participants were seated at a computer desk facing the monitor. Participants were instructed that object manipulation was to occur using only the fingers and not wrist motion. A specified wrist start position was not given to ensure that object manipulation was as natural as possible. Participants were allowed one trial for practice to adopt a comfortable wrist and hand position, ensure a stationary wrist throughout the trials, and familiarize themselves with manipulation of the object in either the normal condition or the simulated amputation condition. Order of condition and order of objects being manipulated were randomized to minimize a potential training or order effect.

The computer reference waveform and the miniBIRD performance trajectories were recorded simultaneously. Data acquisition for the electro-goniometer began prior to the miniBIRD. The participant was instructed to move the object in concert with the moving cursor. For the cork task, participants were instructed to rotate the cork in a clockwise motion (away from the body) to reach the peak of the sinusoidal waveform and in a counter-clockwise (towards the body) motion for the valley of the sinusoidal waveform. For the pen task, participants pushed the pen forward on the wheeled platform to attain the peak and then needed to pull the pen and the wheeled platform backwards in order to reach the valley. The wine task required that participants hold the stem of the glass and tilt the glass forward (away from the body) to reach the peak and backwards (towards the body) to reach the valley. When evaluating the temporal accuracy and amplitude consistency, the peaks and valleys refer to these motions.

Data Analysis

To ensure comparable assessments were made between participants, the middle 9 cycles were chosen for cross-correlation data analysis and filtered with a 4Hz low-pass filter. Using Matlab version 7.1 custom software, each trial was processed and exported for further analysis. To make certain that complete cycles were compared for all participants the first and last cycles of the selected nine were not evaluated, thus seven complete cycles were included for analysis of the data for temporal accuracy and amplitude consistency.

A cross-correlation was performed to compare the performance to reference waveform for each trial. The resultant r-value was used as an index of global performance to compare the normal manipulation to the simulated amputation condition.

Temporal accuracy was analyzed by calculating the phase differences between performance and reference waveforms in milliseconds at both the peaks and the valleys of the sinusoidal pattern. The peak and the valley time (mean ± SEM) were calculated for each trial and object. Outliers were defined by being above 3SD from the mean and were removed from the temporal analysis. The cork task had two outliers that were identified (n=18), the pen task had three (n=17), and the wine task had one (n=19).

Amplitude consistency, expressed as the coefficient of variation (CV) was analyzed by comparing the variability (excursion of movement between peaks and valleys) for each cycle. The coefficient of variation divides the mean by the SD for all cycles and is used as an index of performance.

Raw data collected by the goniometer data was converted to degrees using the conversion formula (Biometrics, Gwent, UK). The total wrist motion for each trial was calculated by subtracting the maximum value from the minimum value for both radial/ulnar deviation and flexion/extension. A composite score was obtained by taking the mean of both movements for all participants and all objects. The mean value of the first 10 data points was used to determine the start position for flexion/extension and radial/ulnar deviation.

The Wilcoxon Signed Rank Test was used to establish statistically significant differences between the two conditions. Statistical significance was determined at $p<0.05$ level.

RESULTS

Gender

Males and females were compared to evaluate changes in age, hand volume and performance for both conditions. There were no significant differences in age between females and males 33.5±7.7 vs 35.1±7.1 years. Table 3 clearly shows that volumeter measurements in males (mean 523±63ml) were significantly greater than females (mean 388±27ml) $p<0.001$. Males performed better on the simulated amputation cork task (median r-value 0.957) compared to females (median r-value 0.900), $p<0.001$. The normal cork manipulation condition showed no significant differences. No other differences in gender were identified.

Cross-Correlation

Cross-correlation is a technique which can be used to compare two waveforms. The resulting r-value ranges from -1 (waveforms are completely opposite) to +1 (waveforms overlap perfectly) and can be used as an index of global performance. The index of performance for the normal manipulation was compared to the simulated amputation condition using the Wilcoxon Signed Rank Test. While performance on the tasks varied between participants, no significant differences were found between the conditions for either the cork task or wine task. However, statistically significant differences were found for performance of the pen task. Manipulation performance in the normal manipulation (median r-value 0.870) was better than in the simulated amputation condition (median r-value at 0.799), p=0.033. Figure 8 shows the r-values for both conditions for each subject. There is little variation between the normal and simulated amputation conditions in performing the cork and wine tasks. In contrast, performance in the pen task was much more variable between the two conditions.

Temporal Accuracy

Temporal accuracy was assessed by computing the time (phase) difference between the performance and reference waveforms in reaching the peaks and valleys of the sinusoidal curve. Table 4 summarizes the number of participants whose timing either lagged or led the reference waveform. Both normal and simulated amputation conditions are shown. Most participants lagged behind the reference waveform. These findings were expected as participants were instructed to follow the cursor.

Temporal Changes During Normal Manipulation

The time (ms) differences between performance and reference waveforms in reaching the peak were compared to the differences in reaching the valleys during the normal manipulation condition. Figure 9 clearly shows that the pen task resulted in statistically significant differences between the peaks and valleys, with the performance peaks consistently more in phase (median 64 ms) with the reference peaks than the valleys (median 93 ms), p=0.003. No differences in timing between the performance and reference peaks and valleys with either the cork or wine task were observed.

Normal and Simulated Temporal Comparison

Figure 10 illustrates the temporal accuracy for both the normal manipulation and the simulated amputation condition. Time differences (ms) between the performance and reference waveforms peaks and valleys were compared between the two conditions. No significant differences in temporal accuracy were found between any of the objects. Similar to the normal condition, performance of the pen task in the simulated amputation condition demonstrated more accuracy in reaching the peaks (median 81 ms) compared to valleys (median 96 ms); however, this was not significant.

Amplitude Consistency

Amplitude excursion between the two conditions was analyzed by comparing the variability between each cycle (excursion of movement between peak to valley) using the coefficient of variation (CV). Figure 11A illustrates a representative expression of the excursion of motion for one cycle. As Figure 11B shows, larger excursions were observed for the wine task on the simulated amputation trials (CV= 1.072) compared to normal manipulation (CV= 0.113) and this was statistically significant (Wilcoxon signed rank test, p<0.001). As the CV takes both the mean and SD into account, the means were compared to ensure that the average excursion was responsible for the observed changes and not the variability within the trial. No significant differences in amplitude excursion were found for either the cork or pen task between the two conditions.

Wrist Motion

All participants selected a starting position of radial deviation and wrist extension, the amount of which varied between each object. Despite changes in the selected pinch posture, the wrist start position did not change. Figure 12 shows the start position participants selected for each object. Figure 12A indicates the start position with respect to radial deviation during the three tasks. Similarly, figure 12B shows the start position for wrist extension. From this start position, amount of motion was recorded. Figure 13 summarizes the amount of wrist motion for all objects and compares normal manipulation to the simulated amputation condition. Although wrist motion occurred, it was minimal and consistent between the two conditions.

DISCUSSION

Visual target pursuit following the trajectory of the waveform is complex. With respect to the overall cross-correlation between the performance and reference waveforms, the pen task was more accurate with a normal pinch posture compared to the simulated amputation condition. This could be explained by familiarity with the tasks. Using the normal pinch posture to hold a pen or utensil is completed many times a day with years of experience. Performing the same task with an unfamiliar pinch posture could account for the decreased accuracy. In addition to task familiarity, the pen task required more complex sensori-motor control demands, as participants needed to use this object as an implement to manipulate the wheeled platform. Compared with the cork and the wine task, the pen task added further sensori-motor control demands with movement on an unstable platform.

When evaluating the patterns for temporal accuracy, the pen task consistently demonstrated increased accuracy on the peaks when compared to the valleys of the sine wave. The peak of the waveform corresponded to pushing the pen and wheeled platform forward. The valley corresponds to pulling the pen backwards and requires constant sensori-motor adjustments to overcome friction from the drag of the wheeled platform. Why this was evident for the pen task and not for the other two tasks may be explained by the different sensori-motor control demands between the in and out phases of the motion. While the pen task had different demands on the in and out phases, the cork and wine task had equal task parameters between the in and out phases. During the pen task, participants needed to focus on the fluidity of movement, the finger manipulation, meeting temporal demands all while maintaining contact with the pen on the unstable platform with constant adjustments necessary to regulate force guided by sensory feedback.

Amplitude consistency was maintained for the cork and pen task but was considerably different for the wine task. This may be explained by the biomechanics of the hand and the increased torque of the glass during tilting. When the index finger is excluded from the wine task, the axis of rotation is changed. The index finger limited excursion in the normal manipulation and without it excursion increased five fold as shown in figure 11B. However, if subjects had followed the speed and height of the cursor, amplitude excursion should be similar between conditions. Whether participants ignored the speed of the cursor or had difficulty controlling the torque due to the unfamiliar pinch posture remains unknown. Future studies need to account for the alteration in biomechanics and perhaps discretely define an amplitude excursion by blocking the object motion in each direction so that optimal comparisons in accuracy can be made.

In addition to hand volume which was expected to be different between males and females, the present study identified gender differences in performance with the simulated amputation in the cork trials with males demonstrating increased accuracy compared to females. The widespread belief is that females are more dexterous than their male counterparts; however, this was not observed in the present study. As only three objects were selected for this study, future research with different objects may generate performance differences between the genders. As the study size was small, generalized conclusions regarding dexterity should be deferred until more research is completed.

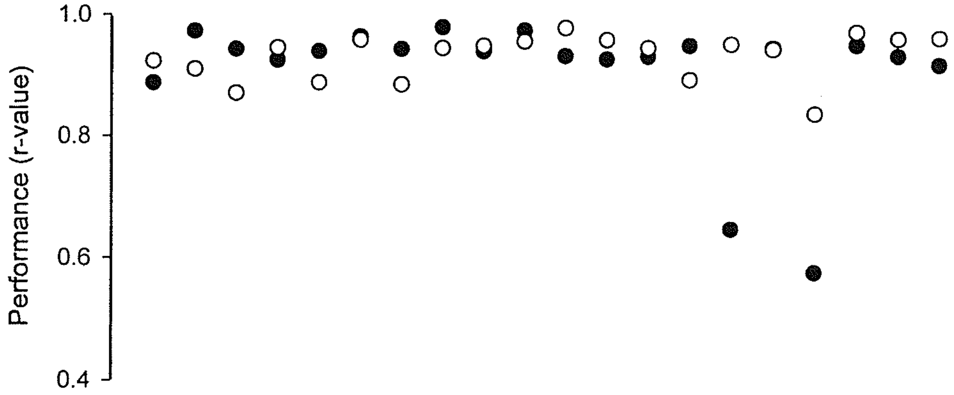
The purpose of the present study was to use highly accurate and sensitive instruments to evaluate changes in temporal and amplitude accuracy in the performance of tasks requiring fine motor manipulation between a normal condition and a simulated index finger amputation condition. Earlier injury-simulated studies sought to answer some of these questions related to hand function after injury, but had used more extreme hand impairments and standardized functional tests that could not capture the quality of object manipulation (Pennathur, 1999;Rondinelli et al., 1997).

Based on the anatomy of the hand, the autonomy of the index finger, its importance in fine motor manipulation, and the frequency of injury, an index finger amputation was selected for simulation in the current study. A limitation of the study would be related to an overestimate of differences and impairments since motor relearning does not occur in the simulation as would in cases of actual amputation. Nonetheless, it would appear that the long finger could easily replace the index finger for many daily functional activities.

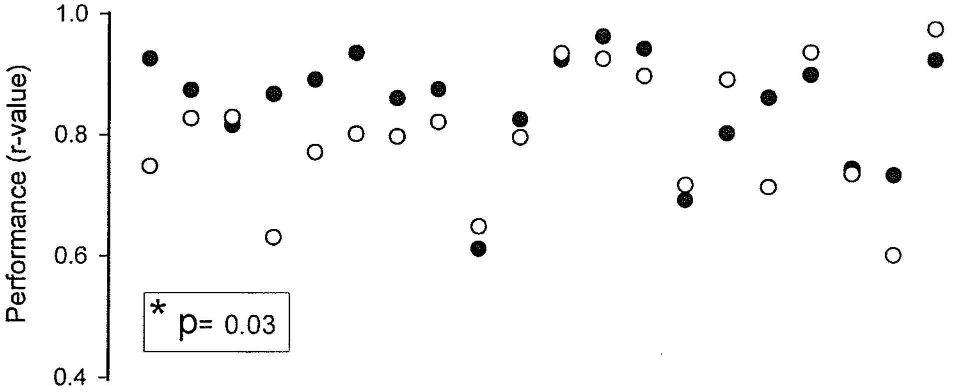
The present study has expanded on previous research on simulated hand injuries by using highly sensitive and accurate tools to quantify changes in movement between two conditions. Tubiana identified the most important of all hand function is the sensory functions of touch and prehension (Tubiana, 1984). Using motion analysis and a sine wave, the grasp phase of prehension can be quantified to improve our understanding of fine motor hand function and the limitations that individuals with finger amputations may face. As therapists, it is important to objectively grade the ability of the hand to function and to assess the phases of approach, grip and release to assist in the safe return to normal daily activities, the workforce and sporting and leisure activities. Future studies should evaluate manipulation of objects further differing in size, weight and texture and include patient populations to evaluate the motor relearning that occurs after injury.

Figure 8. Comparison of Performance in Object Manipulation

A. Cork Task



B. Pen Task



C. Wine Task

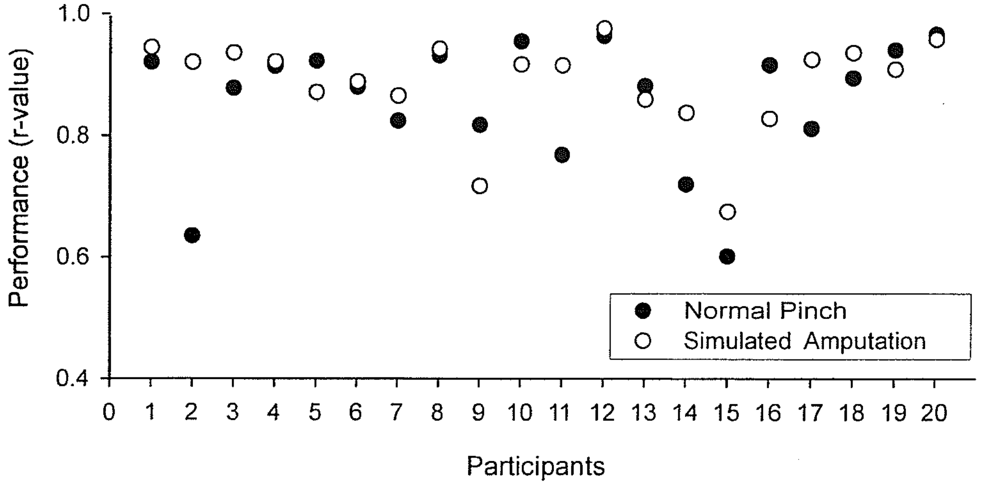


Figure 9. Temporal Accuracy During Normal Object Manipulation

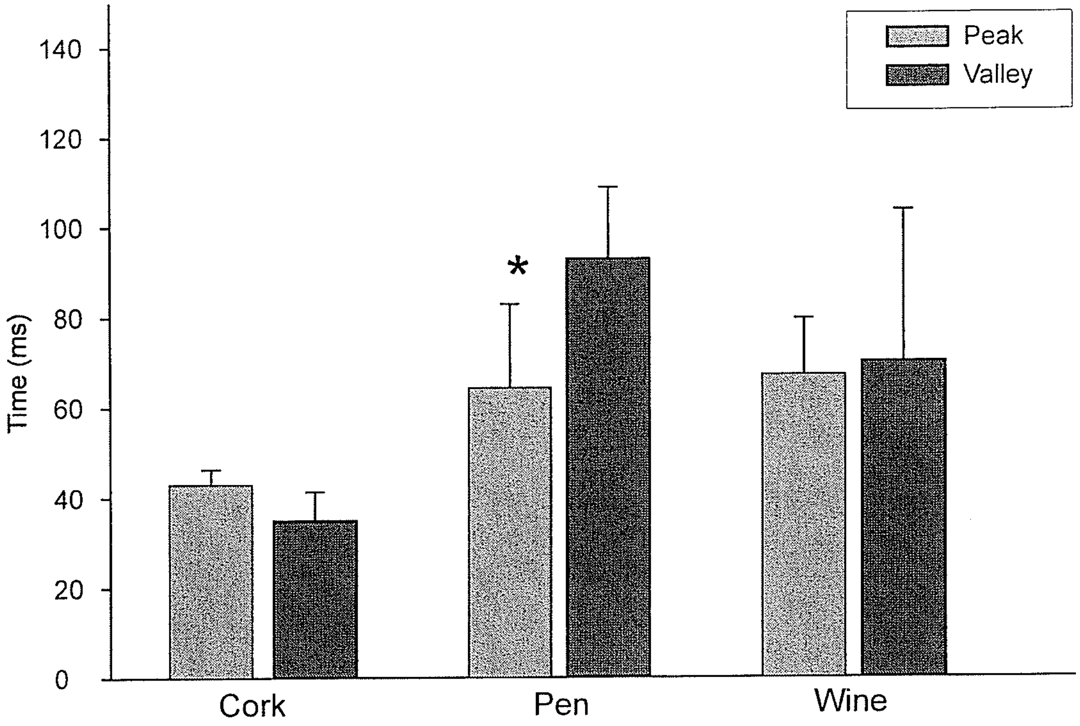


Figure 10. Comparison of Temporal Accuracy Between Normal Manipulation and a Simulated Amputation Condition

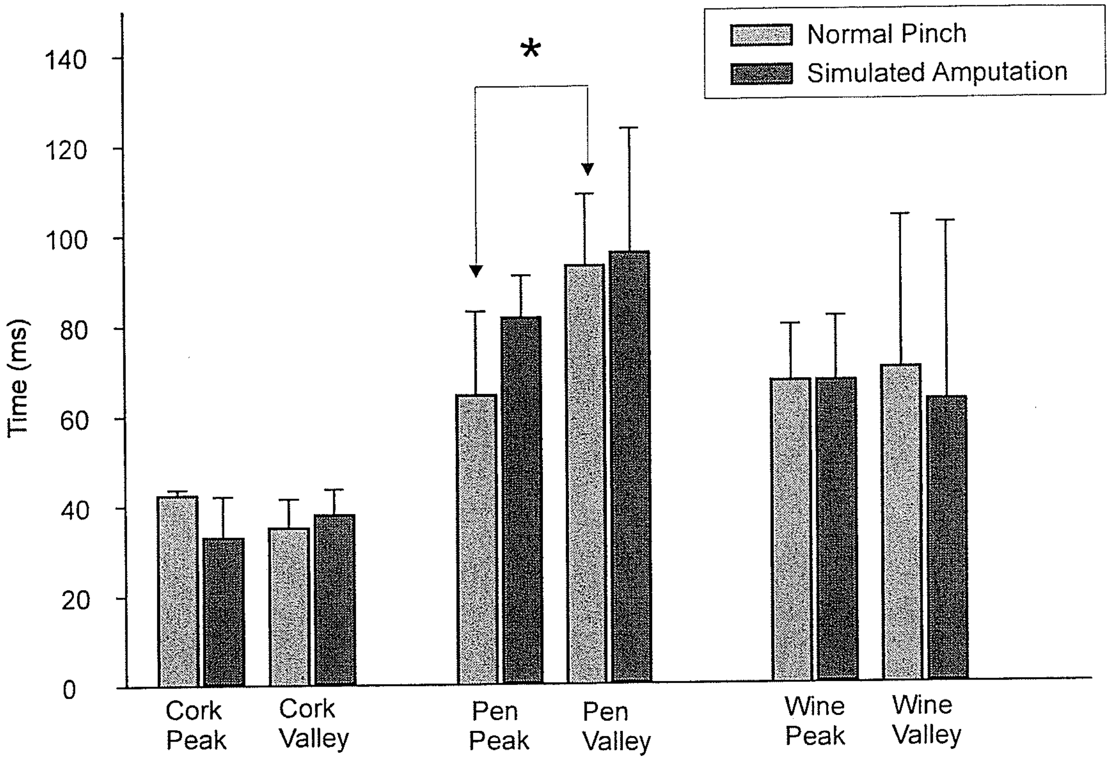


Figure 11. Comparison of Amplitude Excursion between Normal Manipulation and a Simulated Amputation Condition

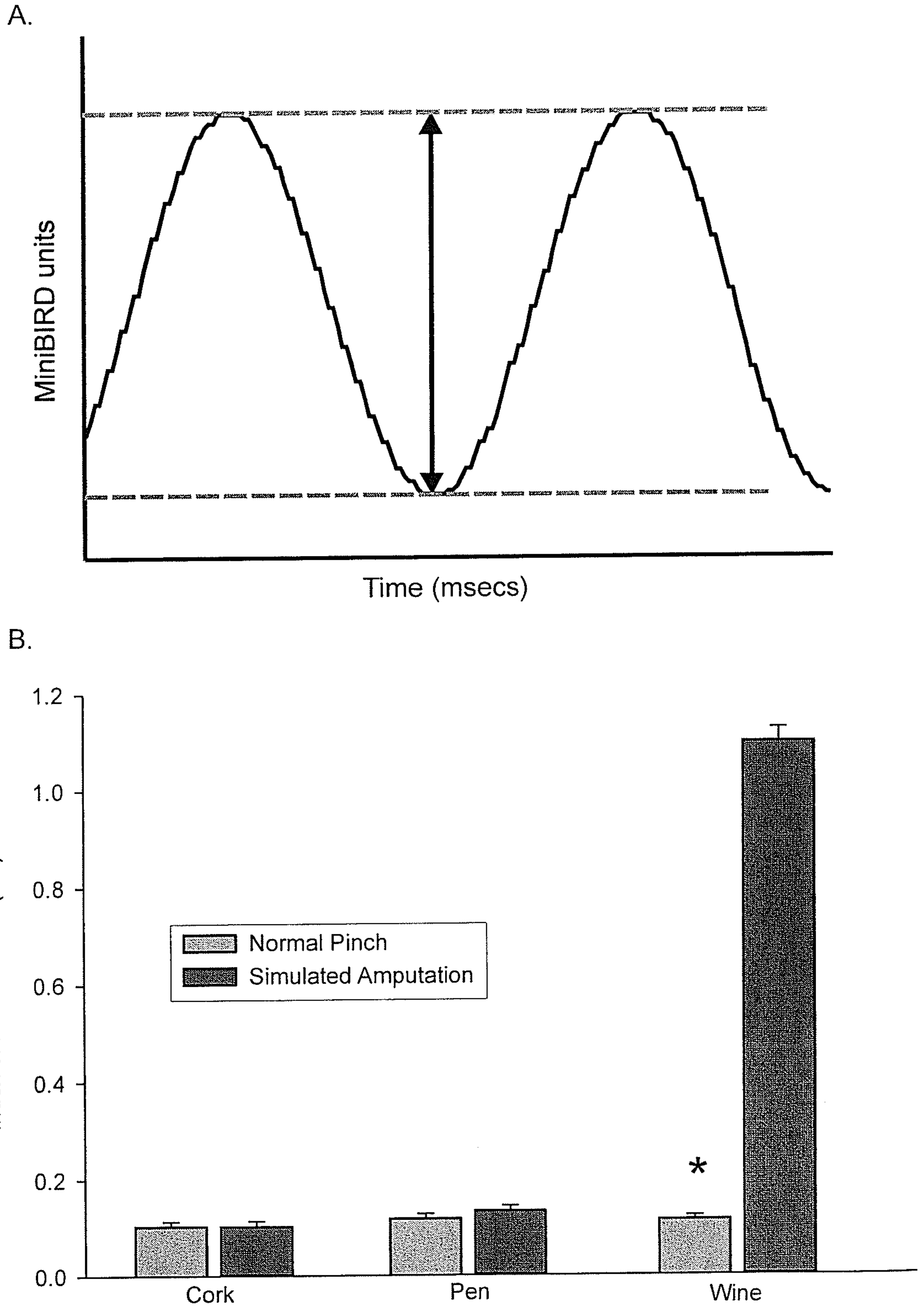


Figure 12. Wrist Start Position

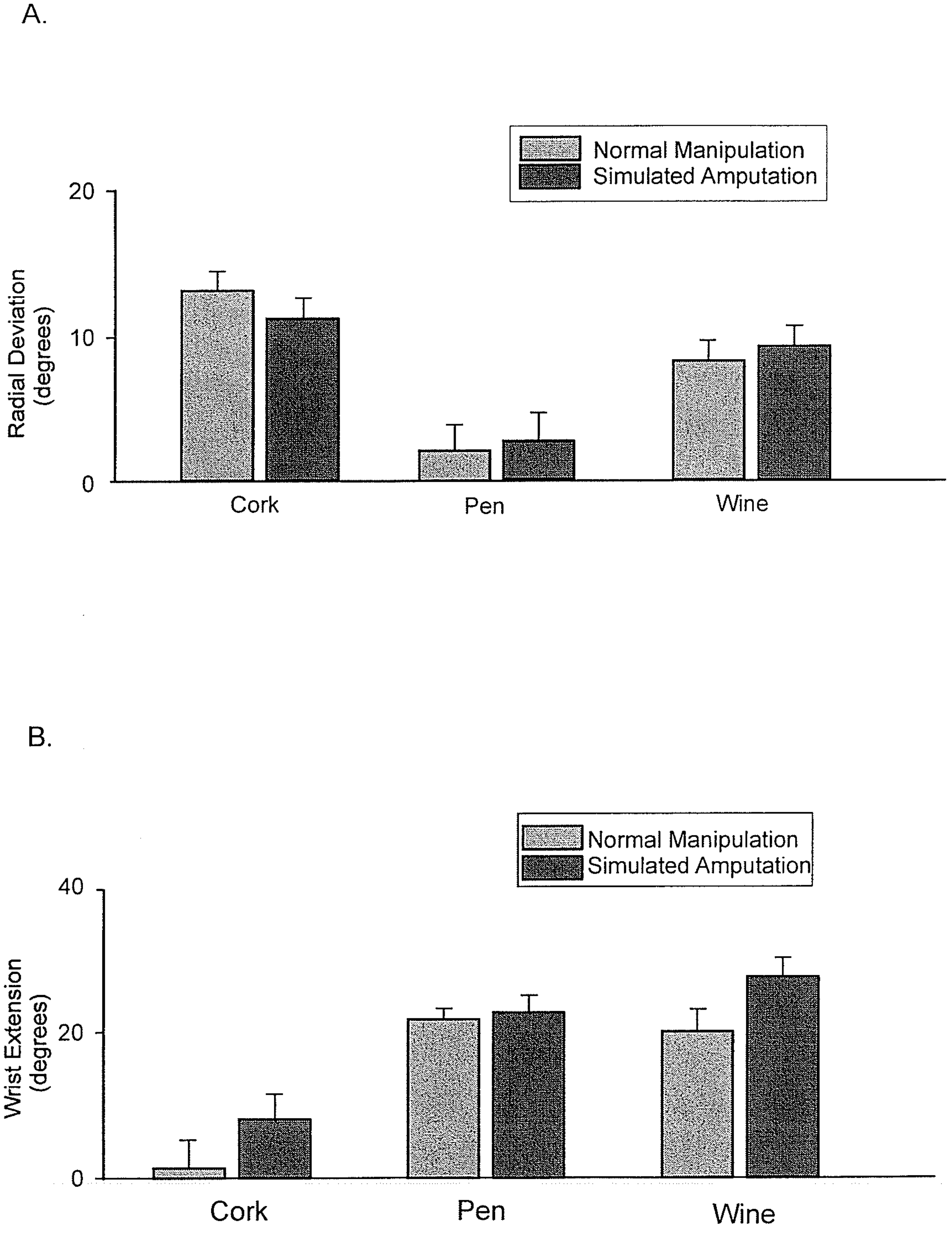


Figure 13. Wrist Motion During Object Manipulation

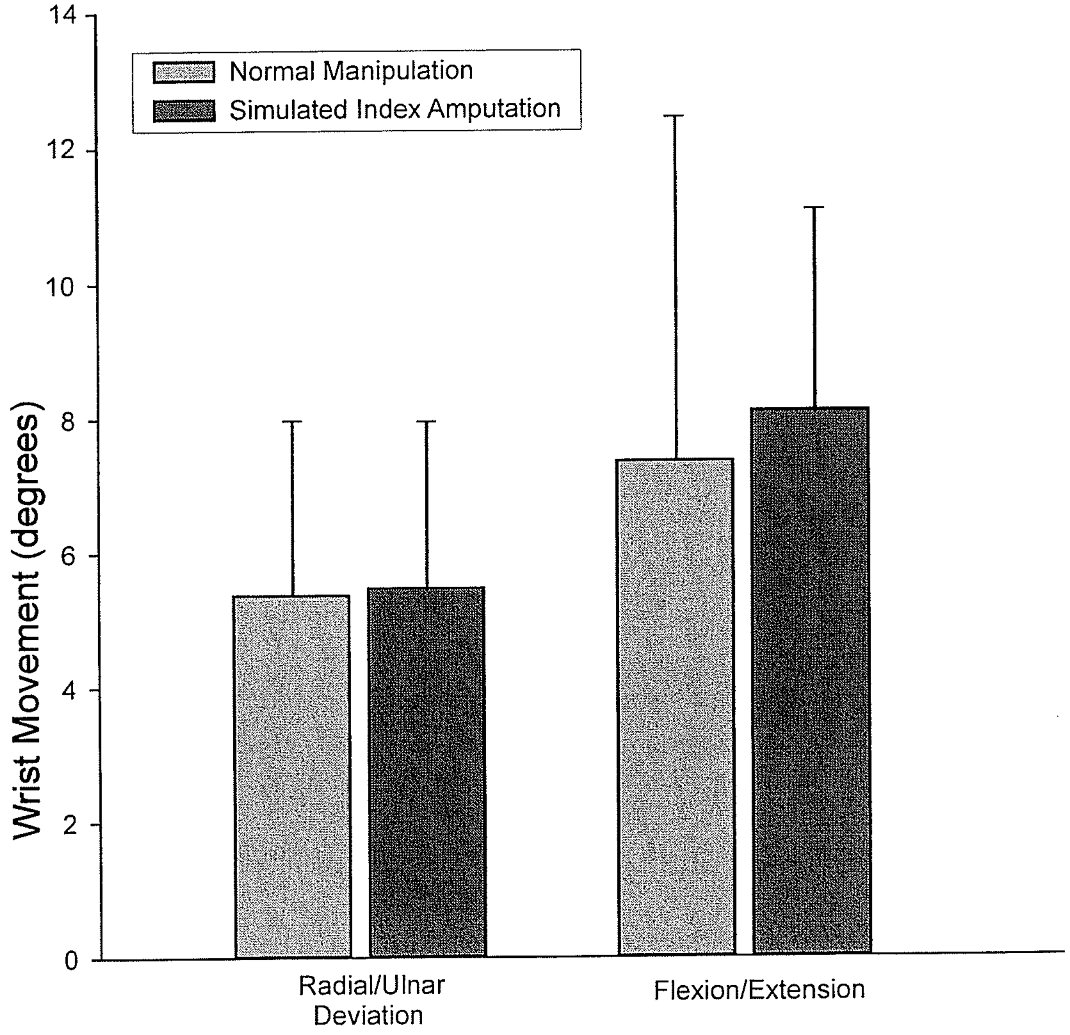


FIGURE LEGENDS

Figure 8. Comparison of Performance in Object Manipulation

This graph compares the overall performance waveform to the reference waveform in the two separate conditions (normal pinch and simulated amputation) for the three objects selected. Figure 1A is the cork task, 1B is the pen task, and 1C is the wine task. R-values obtained from the cross-correlation are used as an index of performance and are shown on the y-axis. The x-axis is each participant (n=20). Closed and open circles represent performance of normal pinch and simulated amputation conditions respectively. Significant differences were found for the pen task with normal manipulation producing more accurate results (r =0.870) compared to the simulated amputation (r = 0.799), p=0.03. There are no significant differences in performance between the two conditions for either the cork or wine task (Wilcoxon signed rank test, NS) indicating that despite an unfamiliar pinch posture participants could follow the waveform as accurately as the normal manipulation condition.

Figure 9. Temporal Accuracy during Normal Object Manipulation

This graph plots the temporal phase shift for object manipulation in the normal condition (cork task n=18, pen task n=17, wine task n=19 participants). Timing differences between the performance and reference sinusoidal waveforms peaks and valleys (mean ± SEM) are compared. The y-axis shows the absolute time difference (ms) and the x-axis indicates the peak (light grey bars) and valley (dark grey bars) for each object manipulation. While the cork task and wine task showed no significant temporal differences between the performance and reference waveform at either the peak or valleys, during the pen task the performance waveform peaks were consistently more in phase with the reference waveform peaks compared to the temporal phase of the valleys (Wilcoxon signed rank test; $p<0.003$).

Figure **10. Comparison of Temporal Accuracy between Normal Manipulation and a Simulated Amputation Condition**

This graph compares the phase shift in object performance for participants using a normal pinch posture (light grey bars) and a simulated index finger amputation posture (dark grey bars). Temporal phase shifts between the reference and performance peaks and valleys of the waveforms (mean ± SEM) are compared (cork task n=18, pen task n=17, wine task n=19 participants). Time (ms) is shown on the y-axis. Objects and waveform peaks and valleys are indicated on the x-axis. There are no significant differences in temporal performance between the two conditions indicating that timing was consistent despite changes in the pinch posture.

Figure **11. Comparison of Amplitude Excursion between Normal Manipulation and a Simulated Amputation Condition**

Figure 11A illustrates a representative expression of the excursion of motion. The peak subtracted by the valley as indicated by the arrow represents the excursion for one cycle. Figure 11B illustrates the relative amplitude excursion during object performance for all participants for normal manipulation and the simulated amputation condition (n=20). The coefficient of Variation (CV) shown as the mean ± SEM is used as an index of performance with respect to the amplitude excursion and is located along the y-axis. Objects are shown on the x-axis. The amplitude excursion remained consistent for the cork task and pen task (NS). Statistically significant differences were found for the wine task with the simulated amputation condition producing more motion than the normal condition (Wilcoxon signed rank test; p= <0.001).

Figure **12. Wrist Start Position**

All the participants selected a starting wrist position of radial deviation and wrist extension. This graph shows the start positions for each task during normal manipulation (light grey bars) and simulated index amputation condition (dark grey bars). Figure 12A illustrates the start position with respect to radial deviation. Degrees are shown along the y-axis and objects are on the x-axis. Values are mean ± SEM for all participants. Similarly, Figure 12B shows mean wrist extension in degrees (y-axis) and objects along the x-axis. Participants chose a consistent start position despite changes in the pinch posture (Wilcoxon signed rank test; NS).

Figure **13. Wrist Motion During Object Manipulation**

This graph compares wrist motion between normal manipulation (light grey bars) and a simulated index finger amputation condition (dark grey bars) for all participants. Bars represent a composite score for deviation and flexion/extension movement for all objects. Deviation is shown on the left and flexion/extension is shown on the right. Values are mean ± SD (n=20). The y-axis is wrist motion (degrees). Wrist motion for both deviation and flexion/extension during object manipulation was consistent between the two conditions (Wilcoxon signed rank test; NS).

TABLES

Table 3. Gender Differences

This table summarizes gender differences. Age, hand size, and performances for the simulated amputation trials are shown. The normal manipulation condition and the clinical dexterity tests are not included as there were no differences identified. Only hand size and the simulated amputation cork task produced significant results when males were compared to females.

	Females	Males	P value
Age (years)	33.5± 2.4	35.1± 2.2	NS
Hand Volume (ml)	388.5± 8.5	523.5± 20.1	P = <0.001
Simulated amputation cork performance (r-value)	0.900	0.957	P = 0.001
Simulated amputation pen performance (r-value)	0.777	0.824	NS
Simulated amputation wine performance (r-value)	0.918	0.912	NS

Table **4. Temporal Changes in Phase – Advance or Delay**

This table summarizes the number of participants whose timing either lagged or lead the reference waveform. Both normal and simulated amputation conditions are shown.

		Cork Task		Pen Task		Wine Task	
		Peaks	Valleys	Peaks	Valleys	Peaks	Valleys
Phase Advance	Normal	4	4	0	2	0	3
	Simulated Amputation	7	4	1	9	0	8
Phase Delay	Normal	14	14	17	15	19	16
	Simulated Amputation	11	14	16	8	19	11

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APPENDIX A

RESEARCH PARTICIPANT INFORMATION AND CONSENT FORM

Title of Study: "Objective evaluation of fine motor manipulation of the hand in normal human subjects".

Principal Investigator:
Ms. Elizabeth Hammond
RR355-800 Sherbrook Street
Winnipeg, Manitoba
R3A 1M4
204-787-1436

Co-Investigators:
Dr. Barbara Shay
RR323A-800 Sherbrook Street
Winnipeg, Manitoba
R3A 1M4
204-787-2756

Dr. Tony Szturm
RR319-800 Sherbrook Street
Winnipeg, Manitoba
R3A 1M4
204-787-4794

You are being asked to participate in a research study. Please take your time to review this consent form and discuss any questions you may have with the study staff. You may take your time to make your decision about participating in this study and you may discuss it with your friends, family or (if applicable) your doctor before you make your decision. This consent form may contain words that you do not understand. Please ask the study staff to explain any words or information that you do not clearly understand.

Purpose of Study

This research study is being conducted to evaluate and grade dexterity of the fingers to move a variety of common household objects used in daily life. Comparisons will be made between a new assessment tool and standard clinical measurement tools.

Objectives

1. To evaluate the reliability of our tool to measure accuracy during object movement
2. To see if other tools commonly used provide the same results
3. To see if the accuracy of movement changes using different fingers to move the objects

A total of 20 participants will participate in this study

Study procedures

Once you decide to participate, you will be asked a few questions including; any previous injuries to your arm, your date of birth, contact number and to confirm you are right handed. Once this information has been collected you will be asked to submerse your hand in water. This is a measure of the size of your hand. Then you will be required to perform two timed tests of dexterity (ability to move objects quickly). These tests take approximately 5 minutes to perform and depending on which test is being completed, it measures how quickly you can place pegs in a board, pick up objects with tweezers and place them in holes, or flip and place wooden coins. These are common tests used in the workplace and in hand therapy to determine how a person performs compared to the larger population. The two tests will then be repeated only this time we will ask that you do not use your index finger to complete the task. This will mimic a finger amputation injury.

We will then measure your accuracy using our tool. Our tool consists of a wave outlined on a computer that we will ask you to follow while grasping a variety of objects with different fingers. All of these objects are familiar in daily life. Some of the objects you will manipulate include a cup, a pen, and a bottle top.

We will show you the direction and speed needed to move the object and allow you to practice in order to familiarize yourself with the task prior to the test. A magnetic sensor is attached to the object and this is what is recording your performance. In addition, you will have small sensors attached to the tips of your fingers to record the pressure you are applying during the task. Finally, a device is attached to the back of your wrist which will measure the amount of wrist movement that occurs during the trial. All of the sensors will be attached with double-sided tape.

In order for us to confirm that our tool is reliable we need you to attend one more session one week later repeating the above. The only difference on this day is that the two timed tests of dexterity will be different than the two you performed previously.

On both of the test days you will be asked to wear a comfortable short sleeve t-shirt. All trials will take place at the School of Medical Rehabilitation Pain Research Laboratory located at RR355-800 Sherbrook Street, Winnipeg, Manitoba.

Participation in the study will consist of two (2) laboratory sessions and will be seven days apart. Each session will take approximately one hour to complete.

You can stop participating at any time. However, if you decide to stop participating in the study, we encourage you to talk to the study staff first. If you are interested in the results of the study you may contact the Principle Investigator at the end of the study.

Discomforts

There may be slight discomfort in removing the tape from the hand and forearm. This will be similar to removing a band-aid.

Benefits

There may or may not be any direct benefit to you from participating in this study. We hope that the information learned from this study will generate further research in investigating hand injuries and provide additional information on the validity of the timed tests currently used.

Costs

All the procedures, which will be performed as part of this study, are at no cost to you.

Payment for Participation

You will receive no payment or reimbursement for any expenses related to taking part in this study.

Confidentiality

Information gathered in this research study may be published or presented in public forums, however your name and other identifying information will not be used or revealed. Despite efforts to keep your personal information confidential, absolute confidentiality cannot be guaranteed. Your personal information may be disclosed if required by law.

The University of Manitoba Health Ethics Research Board may review records related to the study for quality assurance purposes.

All records will be kept in a locked secure area and only those persons identified will have access to these records. If any of your medical/research records needs to be copied to the above, your name and all identifying information will be removed. No information revealing any personal information such as your name, address, or telephone number will leave the University of Manitoba.

Voluntary Participation/Withdrawal from the Study

Your decision to take part in this study is voluntary. You may refuse to participate or you may withdraw from the study at any time. Your decision not to participate or to withdraw from the study will not affect your care at this centre. If the study staff feel that it is in your best interest to withdraw you from the study, they will remove you without your consent.

We will tell you about any new information that may affect your health, welfare, or willingness to stay in this study. Participants who are students or employees of either The University of Manitoba or Health Sciences Centre or individuals associated professionally with any of the investigators can be assured that a decision not to participate will in no way affect any performance evaluation of potential participants.

Medical Care for Injury Related to the Study

You are not waiving any of your legal rights by signing this consent form nor releasing the investigator(s) from their legal and professional responsibilities.

Questions

You are free to ask any questions that you may have about your treatment and your rights as a research participant. If any questions come up during or after the study or if you have a research-related injury, contact the principle investigator: Elizabeth Hammond at

For questions about your rights as a research participant, you may contact The University of Manitoba, Bannatyne Campus Research Ethics Board Office at (204) 789-3389

Do not sign this consent form unless you have had a chance to ask questions and have received satisfactory answers to all of your questions.

Statement of Consent

I have read this consent form. I have had the opportunity to discuss this research study with Elizabeth Hammond and Dr. Barbara Shay or her study staff. I have had my questions answered by them in language I understand. The risks and benefits have been explained to me. I believe that I have not been unduly influenced by any study team member to participate in the research study by any statements or implied statements. Any relationship (such as employer, supervisor or family member) I may have with the study team has not affected my decision to participate. I understand that I will be given a copy of this consent form after signing it. I understand that my participation in this study is voluntary and that I may choose to withdraw at any time. I freely agree to participate in this research study.

I understand that information regarding my personal identity will be kept confidential, but that confidentiality is not guaranteed. I authorize the inspection of any of my records that relate to this study by The University of Manitoba Research Ethics Board, for quality assurance purposes.

By signing this consent form, I have not waived any of the legal rights that I have as a participant in a research study.

______I agree to be contacted for future follow-up in relation to this study,
Yes _ No _

Participant signature__________________________ Date
____

(day/month/year)

Participant printed name: _____________________________

I, the undersigned, have fully explained the relevant details of this research study to the participant named above and believe that the participant has understood and has knowingly given their consent

Printed Name: ___________________________________Date
____

(day/month/year)

Signature: _____________________________

Role in the study: _____________________________

Relationship (if any) to study team members:_______________________