COMPARISON OF TRAPEZIOMETACARPAL JOINT MOTION BETWEEN GENDERS USING MULTIPLE MEASUREMENT TECHNIQUES

by

Robert L. Hulbert

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Robert L. Hulbert

Approved: ____
James G. Richards, Ph.D.
Professor in charge of thesis on behalf of the Advisory Committee

Approved: ____
William Farquhar, Ph.D.
Chair of the Department of Kinesiology and Applied Physiology

Approved: ____
Kathleen Matt, Ph.D.
Dean of the College of Health Sciences

Approved: ____
James G. Richards, Ph.D.
Vice Provost for Graduate and Professional Education

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ABSTRACT

Thumb function accounts for up to 50 percent of total hand function with most of its function coming from the trapeziometacarpal (TMC) joint, located at the base of the thumb between the first metacarpal and trapezium. The TMC joint is unique in that it has two non-intersecting, non-orthogonal axes of rotation that generate three distinct motions; flexion/extension, abduction/adduction and pronation/supination. Past studies have analyzed overall ROM of the TMC joint by simultaneously measuring maximal planar and composite motions, which together form a spherical surface area used to find the maximal workspace. However, none of these studies have compared their results with range of motion (ROM) or workspace measurements obtained during clinical tests such as the thumb opposition portion of the Modified Kapandji Index (MKI), which is designed to measure the thumb component of overall hand mobility. Analysis of TMC kinematics is also important in identifying potential risk factors of TMC osteoarthritis (OA), one of the most common diseases of the hand. TMC OA is believed to be caused by increased joint ROM, and has been shown to be more prevalent in the female population. However, past studies analyzing TMC kinematics between genders have shown mixed results, so it becomes imperative to determine if females display significantly greater TMC ROM and workspace than males.

The purpose of this study was to determine the difference in ROM and workspace measurements at the trapeziometacarpal joint between genders using multiple measurement techniques. An eight camera motion capture system was used to track the location of retroreflective markers placed on the wrist, hand, and thumb. Based on these marker locations, coordinate systems for the wrist, hand, and thumb were built. TMC axis orientation and TMC workspace were then calculated using custom software written in LabVIEW and Matlab.

Comparisons between the MKI task and Max TMC task showed that the MKI task displays significantly less abduction/adduction ROM (p=.038) and workspace (p=.045) than the Max TMC task. Comparisons between genders for each of the measured motions showed no significant differences in TMC ROM in either of the TMC axes. Comparisons between genders during each of the multi-movement tasks (MKI and Max TMC) showed no significant differences in TMC workspace.

These results indicate that increased mobility is not a viable explanation for the increased likelihood of developing TMC OA in the female population, which raises further research questions aimed at determining the TMC joint differences between genders which may explain the discrepancy in TMC OA development. These results also prove that the clinical MKI test is ineffective in measuring the entire ROM and workspace of the thumb. This means that it may need to be done in unison with other tests to ensure that the patient is exploring a greater amount of their available TMC abduction/adduction ROM and workspace. This information is important to both

clinicians and patients as it may help to improve on the process of clinically measuring and evaluating thumb ROM and function in injured and pathological populations.

While this research has proven beneficial in determining kinematic differences between healthy populations, future research should focus on the development of an accurate musculoskeletal model of the human thumb with the ability of assessing both kinematic and kinetic parameters. This would prove to be a valuable tool that could be used to track the onset and progression of thumb related pathologies as well as make comparisons between different subject populations, such as individuals with healthy TMC joints and individuals with osteoarthritic TMC joints. This future thumb model would also be a monumental tool which could be used by surgeons and clinicians to optimize pre-surgical planning and assess different treatment outcomes at an individual patient level.

Chapter 1

SPECIFIC AIMS

The purpose of this study was to determine the difference in range of motion (ROM) and workspace measurements at the trapeziometacarpal joint between genders using multiple ROM measurement techniques.

Thumb function accounts for up to 50 percent of total hand function with most of its function coming from the trapeziometacarpal (TMC) joint, located at the base of the thumb between the first metacarpal and trapezium [1-3]. The TMC joint is unique in that it has two non-intersecting, non-orthogonal axes of rotation that generate three distinct motions; flexion/extension (flex/ext), abduction/adduction (abd/add) and pronation/supination (pro/sup) [1]. The anatomical structure of the TMC joint allows for pure flex/ext, abd/add, as well as composite circumduction and opposition motions which play a crucial role in hand prehension [3]. Due to the complexity of the TMC joint, measurement of TMC kinematics is challenging. However, recent efforts have demonstrated that it is possible to accurately measure in vivo TMC kinematics, three dimensionally, using retroreflective markers carefully placed on the surface of the thumb and hand [4-6].

Past studies have analyzed overall ROM of the TMC joint by simultaneously measuring maximal planar and composite motions, which together form a spherical surface area used to find the maximal workspace [3,7-9]. However, none of these studies have compared their results with ROM or workspace measurements obtained during clinical tests such as the thumb opposition portion of the Modified Kapandji Index (MKI), which is designed to measure the thumb component of overall hand mobility [10]. By measuring the ROM of the TMC joint during the thumb opposition portion of the MKI, the effectiveness of the MKI as a clinical measure of TMC ROM and workspace can be evaluated. Analysis of TMC kinematics is also important in identifying potential risk factors of TMC osteoarthritis (OA), one of the most common diseases of the hand [11]. TMC OA is believed to be caused by increased joint ROM, and has been shown to be more prevalent in the female population [11-16]. However, past studies analyzing TMC kinematics between genders have shown mixed results, so it becomes imperative to determine if females display significantly greater TMC ROM and workspace than males [4,6,8,17,18]. This would identify whether females have an increased potential for developing TMC OA due to increased joint ROM and would provide an explanation for the greater prevalence of TMC OA that is currently seen in females.

The expected outcomes of this study include: 1. An assessment of the ability of the MKI to measure maximal TMC joint ROM and workspace. 2. A definitive answer to whether the amount of TMC joint ROM and workspace is different between genders. The MKI was evaluated on its effectiveness in measuring maximal TMC ROM and workspace to determine its usefulness in assessing thumb motion clinically. Outcomes also allow conclusions to be drawn about maximal TMC joint ROM and workspace differences between genders, with larger ROM and workspace being associated with the development of TMC OA [11-15].

<u>Specific Aim 1:</u> Compare the maximal TMC ROM and workspace during the MKI with maximal TMC ROM and workspace during maximal planar (flex/ext, abd/add) / composite (circumduction, opposition) thumb motions.

Hypothesis 1.1: Maximal TMC ROM will be significantly less in each TMC rotation axis during the MKI than maximal TMC ROM during the maximal planar/composite motions.

Hypothesis 1.2: Maximal TMC workspace will be significantly less during the MKI than maximal TMC workspace during the maximal planar/composite motions.

<u>Specific Aim 2:</u> Determine maximal TMC joint ROM differences between genders using planar, composite, planar/composite, and MKI ROM measurements.

Hypothesis 2.1: The female group will display significantly greater TMC joint ROM about the primary axis of rotation for all maximal planar ROM measurements (i.e. greater flex/ext ROM when performing maximal flex/ext ROM measurement).

Hypothesis 2.2: The female group will display significantly greater TMC joint ROM in both TMC rotation axes during maximal composite, maximal planar/composite, and MKI ROM measurements.

<u>Specific Aim 3:</u> Determine maximal TMC workspace differences between genders using the combined spherical area measured from the maximal planar/composite thumb motions and the MKI thumb motions.

Hypothesis 3.1: The female group will display significantly greater TMC workspace during the maximal planar/composite thumb motions and the MKI thumb motions.

Chapter 2

BACKGROUND AND SIGNIFICANCE

The human hand has a total of 27 bones making up five sequential links. These links are numbered in order, one through five, one being the thumb and five being the pinky finger. Each Finger (2-5) is made up of four bones; metacarpal, proximal phalange, middle phalange, and distal phalange. The thumb is made up of three bones; metacarpal, proximal phalange, and distal phalange. The remaining eight bones of the hand are the carpal bones which form the link between the fingers/thumb and the rest of the arm [19,20]. Articulations between the carpal bones and metacarpals form the carpometacarpal (CMC) joints which connect the wrist with the thumb/fingers and in some cases are essential in providing motion. Links between the metacarpals and phalanges form the metacarpal-phalangeal (MCP) joints, and links between the phalanges form the interphalangeal (IP) joints [19].

Nearly fifty percent of overall hand function is appropriated by the thumb, making it the most important digit of the hand [3,21-24]. A stable, healthy thumb plays an important role in a variety of everyday tasks such as gripping, grasping, and pinching both small and large objects [25]. The thumb is dissimilar in structure having only three bones and three articulations (CMC, MCP, and IP), compared to the fingers which have four bones and four articulations (CMC, MCP, proximal IP, and distal IP) [19]. The CMC joint of the thumb known more specifically as the trapeziometacarpal (TMC) joint is different from the CMC joints of the fingers due to its unique joint structure and range of motion. The TMC joint consists of the first metacarpal and trapezium, whose concave-convex surfaces articulate to form a saddle joint [26]. The saddle shape allows the TMC joint to display specific motion patterns not seen in the other joints of the thumb or hand, making it the most important and functional joint in the thumb [2,3,23,24,27].

Clinically, the motion of the thumb has been classified through various methodologies. One of the simplest methods used involves measuring the distance between the flexor crease of the thumb IP joint and flexor creases of the palm of the hand. While this technique is relatively simple to perform it only allows measurements of overall thumb displacement in relation to the rest of the hand [3]. A common clinical tool used for evaluating joint ROM is a manual goniometer, but ROM measurements at the thumb are complex and methods for accurate goniometer measurements are lacking [3,10]. The Hexatron, a goniometer specifically designed to measure thumb ROM, evaluates thumb movements based on a 3D linkage mechanism, allows free motion at the thumb, and tracks the motion of the first metacarpal and phalanx [3,7,28]. However, it does not allow for assessment of individual joint orientation and rotation during thumb motion [3,25].

The predominant clinical test for assessing thumb and finger function is the MKI. This test has three parts, two measuring long finger flexion and extension, and the other measuring thumb opposition and counter-opposition [10]. These three tests are designed to measure overall hand mobility; with the thumb opposition portion designed to measure the overall thumb mobility of the hand. The thumb opposition portion of the MKI is scored from 0 to 10 and is based on the individual's ability to oppose different aspects of the hand, with a higher score corresponding to a greater functional ability to produce opposition [10,29]. The lowest score, a zero, indicates the ability to oppose the thumb to the lateral side of the proximal index phalanx, while the highest score, a ten, indicates the ability to oppose the thumb to the distal volar crease of the hand [10]. While this test provides beneficial measurements of overall thumb mobility it lacks the ability to quantitatively measure individual joint orientations and rotations [2,4]. Due to its specialized nature, the MKI may also lack the ability to assess the entire ROM of the thumb and is occasionally combined with other gripping and grasping tests to ensure the assessment of the entire thumb ROM [30]. Past studies have not quantitatively assessed the effectiveness of the MKI in measuring TMC ROM or workspace. By measuring the three dimensional kinematics of the TMC joint during the MKI it helps to shed light onto the usefulness of the MKI as a clinical measure of thumb ROM.

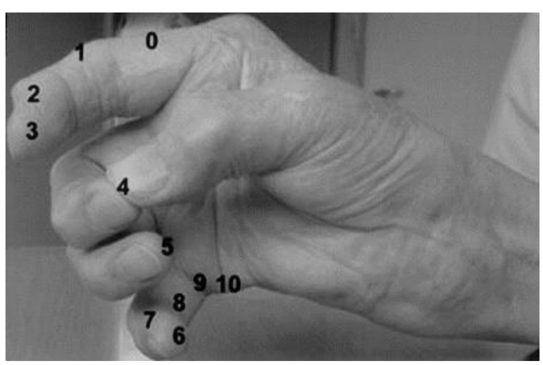

Figure 1: Diagram of the Modified Kapandji Index scoring system [10]

TMC ROM can occur about the flexion/extension (flex/ext) and abduction/adduction (abd/add) axes. It is unique to the other joints of the hand in that for any flex/ext or abd/add movement there is also a paired pronation/supination (pro/sup) movement [1]. This paired axial rotation allows the thumb, as a whole to move through circumduction and opposition which are crucial for proper thumb and hand function [1,3]. Previously, the TMC joint has been modeled as a universal joint with orthogonal and intersecting degrees of freedom (DoF) and one center of rotation [18,31]. However, recent research suggests that there may be inaccuracies in these earlier models [1,22,32]. The anatomical saddle shape of the adjoining metacarpal and trapezium suggest that the TMC joint may be modeled more accurately with non-interesting, non-orthogonal axes of rotation that describe rotation about the trapezium and head of the metacarpal separately [1,22,33-35]. Helical axes obtained during testing of TMC motion indicate two primary axes, flex/ext and abd/add, which are non-intersecting and are located about 5 mm from one another [1,22,33]. The flex/ext axis traverses the trapezium and is located ulnarly with respect to the abd/add axis which traverses the proximal head of the first metacarpal [1,22]. Simultaneous rotation about both primary axes causes a skew, considered by some to be a rotation about an additional axis (pro/sup) [33].

Chang and Pollard have created a 3 DoF model to account for flex/ext, abd/add, and pro/sup in the TMC joint. The model has two non-intersecting, non-orthogonal axes representing flex/ext and abd/add, as well as a third pro/sup axis whose rotation represents the relative skew between the other two axes. During thumb motion this model has shown an average pro/sup of 23 degrees during TMC motion [33]. This finding goes against past literature which suggests that pro/sup of the TMC joint can only occur passively [18]. Cooney et al. reported that during active motion, the muscle forces and compressive forces acting at the thumb constrain the TMC joint in such a way that pro/sup is not considered to be a DoF [18]. Accounting for this anatomical consideration, Cerveri et al. modeled the TMC joint with two functional DoF representing the non-orthogonal, non-intersecting axes of flex/ext and abd/add. This model does not consider pro/sup as a functional DoF but instead assumes that a unique pro/sup twist is generated during simultaneous rotation about the non-orthogonal, non-intersecting flex/ext and abd/add axes [1]. This model outperformed universal joint models in predicting ROM in the flex/ext and abd/add axes [1]. When compared to true joint motion obtained from magnetic resonance imaging (MRI) analysis this model produced joint motion comparable to the MRI measured joint motion [22].

Previous studies, both in vivo and in vitro have validated the use of surface markers to accurately measure TMC kinematics, showing minimal errors due to soft tissue movement [1,2,36]. The ability to accurately measure TMC kinematics opens the door for a substantial amount of clinical research pertaining to various pathological thumb disorders, such as TMC osteoarthritis (OA). Osteoarthritis of the TMC joint is a frequent form of OA and is one of the most common diseases involving the hand [11,16]. Previous research has shown that excessive mobility may be a significant factor in the development of osteoarthritis, due to increased biomechanical loads placed on the

TMC joint surfaces [12,14,23]. Over time, excessive mobility can lead to decreased joint space and increased pain, eventually requiring surgery if conservative measures are not sufficient to relieve pain and return the thumb to normal function [13,14,23]. Trapeziometacarpal OA is ten times more likely to occur in women than in men, with symptoms typically developing by the fifth or sixth decade of life [16,23]. While it is commonplace that generalized joint laxity and ROM is greater in females, differences in mobility between genders in the TMC joint are not well known [12,37]. In fact, previous studies have shown mixed results as to which gender has greater ROM at the TMC joint [4,6,8,17,18]. By quantifying the three-dimensional TMC kinematics, comparisons of TMC ROM and workspace can be made between genders. Significant ROM and workspace differences would indicate increased joint laxity in one of the genders, indicating a potentially greater risk for developing TMC OA in that gender [11-15]. By identifying this difference it helps to inform the at-risk population of the increased chance of developing TMC osteoarthritis, so that preventative measures such as therapy or surgery can be taken prior to the onset of degenerative arthritis [23, 38].

The abundance of upper extremity disorders has become an important occupational health issue across all industry sectors accounting for up to 33 percent of lost work day injuries in the manufacturing industry alone [5,39]. Since TMC OA has been shown to be one of the most common musculoskeletal disorders in the upper extremity it becomes evident that there is a need to accurately model human thumb motion to determine its biomechanical function in everyday life [11,40]. An accurate musculoskeletal thumb model will help to determine the role of thumb motion and loading in the onset and progression of OA and other thumb related pathologies. It will also provide surgeons and clinicians with a valuable tool that can be used to optimize pre-surgical planning and quantifiably evaluate the effectiveness of different treatment interventions. Results of this proposed study along with future research combining thumb kinematics and musculoskeletal modeling will accelerate the development of an accurate musculoskeletal thumb model, ultimately increasing the functional ability and quality of life in patients with thumb pathologies.

Chapter 3

METHODS

Subjects

The study population consisted of 12 females and 12 males, between the ages of 18 and 40. The average age of the male subjects was 25.7 ± 3.7 and the average age of the female subjects was 25.1 ± 3.6. This age range represents a population that has gone through the stages of puberty but has yet to go through the stages of menopause, in the case of the female subjects. Both of these events are marked by major hormonal changes which have been shown to effect ligament laxity [37, 41]. Data collection was performed on the dominant hand of all subjects unless a current or past hand injury or pathology had occurred in the dominant hand, in which case the non-dominant hand was tested. All subjects were recruited on the University of Delaware campus and completed a medical questionnaire prior to being included in the study. The questionnaire was used to identify those who had a current or past hand injury or pathology in their dominant hand. In the event of an injury or pathology in both hands, the individual was excluded from the study. Informed consent procedures were followed in accordance with the institution's human subjects review board.

Data Collection

An eight camera motion capture system (Motion Analysis Corporation, Santa Rosa, CA, USA) operating at 60 Hz was used to track the three dimensional locations of retro-reflective surface markers. In order to calculate TMC kinematics, nine 6mm retro-reflective markers were placed on the specific landmarks of the thumb, wrist, and hand depicted in Table 1. Sixteen additional 6mm retro-reflective markers were placed on landmarks of the thumb, wrist, and hand as depicted in Table 2. These markers were used to measure additional joint motions that may have occurred during data collection. All surface markers were attached to the skin using manual palpation techniques that have been previously validated to accurately track TMC kinematics [2, 36].

Table 1 – Location of the retro-reflective markers that were used to calculate TMC kinematics

Thumb Markers (3)	Wrist Landmarks (3)	Hand Dorsum Markers (3)
Proximal first metacarpal head	Radial styloid process	Distal end of second metacarpal
Distal first metacarpal head - Radial side	Ulnar styloid process	Distal end of third metacarpal
Distal first metacarpal head - Ulnar side	Dorsal center of forearm	Proximal end of third metacarpal

Table 2 – Location of the additional markers used to measure additional joint motion that may occur during data collection.

Thumb Markers (2)	**Hand Markers (2)**	**Finger Markers (12)**
Dorsal surface of IP joint	Distal end of fourth metacarpal	Dorsal surface of proximal IP joints 2-5
Dorsal surface of thumb tip	Distal end of fifth metacarpal	Dorsal surface of distal IP joints 2-5
		Dorsal surface of finger tips 2-5

Following marker attachment, the subjects were seated in a chair, which was adjusted to allow the forearm to rest comfortably on a table in a neutral position, with the elbow flexed at about 90 degrees. To limit arm movement during data collection, a strap was placed over the forearm six inches proximal to the center forearm marker. Joints in the hand, fingers, and thumb were not constrained so that natural TMC motion could be captured. The TMC motions were separated into single movements and multi-movements and are described in Table 3. During each of these motions, other than the thumb opposition portion of the MKI, subjects were instructed to avoid motion in the other joints of the fingers (2-5) and hand. Prior to actually collecting data, each TMC motion was demonstrated and subjects were given ample time to practice each motion.

Table 3 – TMC motions separated by single and multi-movement. Descriptions of each of the six motions are also provided.

Single Movements	**Description**
Flexion/Extension	Maximal frontal plane motion of the TMC joint, parallel to the palm (flexion towards the palm of hand)
Abduction/Adduction	Maximal motion of the TMC joint in a plane perpendicular with the palm of the hand
Opposition-Reposition	Maximal motion of the TMC joint towards the MCP of the pinky finger and back to full extension
Circumduction	Maximal motion of the TMC joint in two counterclockwise circles
Multi-Movements	
Maximal TMC	Maximal motion of the TMC joint in flex/ext, abd/add, opposition, and circumduction
Modified Kapandji Index (Opposition)	Thumb motion performed by touching the thumb tip to 11 specific locations on the hand

During data collection, three continuous trials of each single TMC motion were completed and three trials of each multi TMC motion were completed with 30 seconds of rest between each trial to reduce the effects of fatigue. During the single movements, each subject started and ended with the thumb in a self-selected neutral position. During the Maximal TMC movement, each subject was instructed to perform one of the four maximal motions starting with flexion/extension and ending with circumduction. During each of the four maximal motions the subject started in their self-selected neutral position and returned to their neutral position prior to performing the next maximal motion. During the MKI each subject was instructed to perform each part of the test in order from zero to ten, starting in a counter-opposition (reposition) position and returning to the counter-opposition position prior to performing the next part of the test. The order of single and multi-movements was randomized for each subject in an effort to minimize the effects of fatigue. Following data collection, kinematic data was analyzed using custom software written in LabView (National Instruments, Austin, TX, USA) and Matlab (MathWorks, Natick, MA, USA).

Data Analysis

Trapeziometacarpal joint motion was analyzed to determine the three dimensional orientation of two non-intersecting, non-orthogonal axes representing flex/ext and abd/add [1,34,35]. The nine retro-reflective surface markers, depicted in table 1, were used to define three separate coordinate systems (CS); the wrist CS, the hand CS, and the thumb CS. The wrist CS was located at the midpoint of the line joining the radial and ulnar styloid process markers [1]. The vector joining the midpoint of the wrist and the marker placed on the dorsal aspect of the forearm represented the Y axis. The Y axis was crossed onto an intermediate vector created by joining the radial styloid process marker and the dorsal forearm marker, which represented the Z axis of the wrist CS. The Y axis was then crossed onto the Z axis to obtain the X axis of the wrist CS. The hand CS was located at the proximal third metacarpal. The Y axis of the hand CS was computed from the vector joining the proximal and distal third metacarpal markers. The Y axis was crossed onto an intermediate vector created by joining the markers located on the distal second metacarpal and proximal third metacarpal, which represented the Z axis of the hand CS. The Y axis was then crossed onto the Z axis to obtain the X axis of the hand CS. The thumb CS was located at the proximal third metacarpal. The vector joining the proximal first metacarpal marker and the midpoint of the distal first metacarpal markers represented the Y axis of the thumb CS. The Y axis was crossed onto an intermediate vector created by joining the marker located on the radial side of the distal first metacarpal and the marker located on the proximal first metacarpal, which represented the Z axis of the thumb CS. The Y axis was then crossed onto the Z axis to obtain the X axis of the thumb CS (Figure 2). The hand CS was used to detach thumb motion from hand motion so that the flex/ext and abd/add orientations could be determined [1]. After defining each CS, helical angles were used to resolve the correct orientations about the axes of the thumb CS. These enabled the accurate determination of the flex/ext and abd/add components of TMC motion throughout each of the measured single and multi-movements.

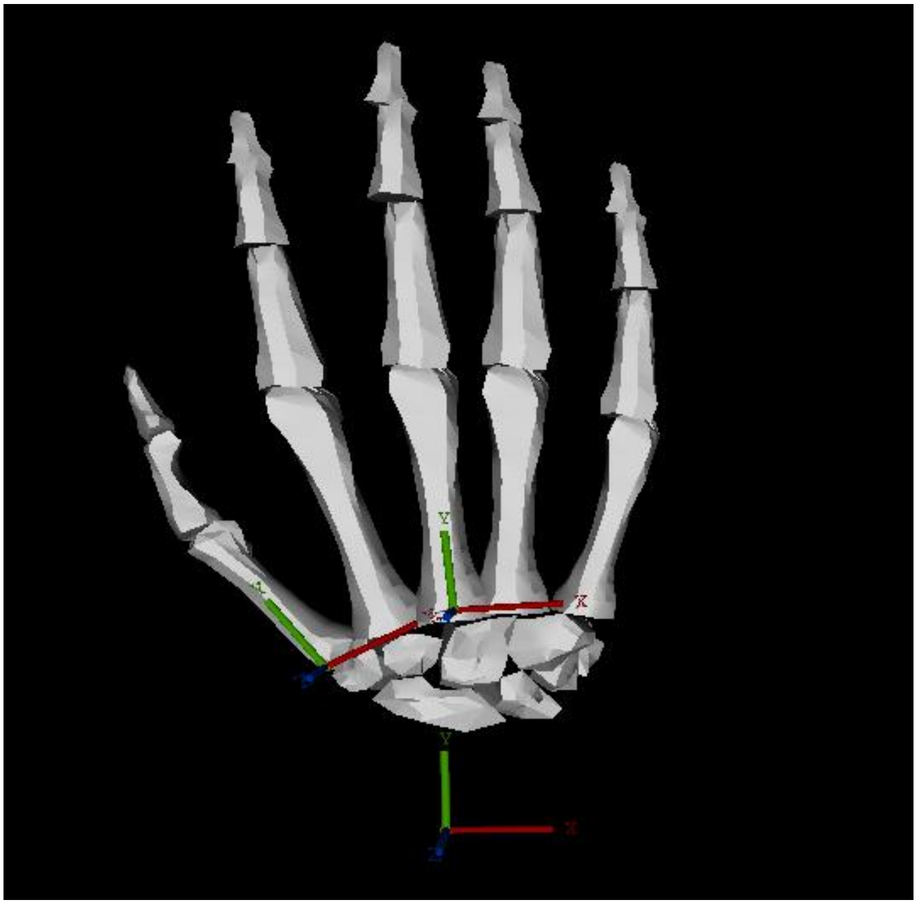

Figure 2: View of the hand with 3-D coordinate systems located at the wrist (radius and ulna not pictured), proximal third metacarpal, and proximal first metacarpal.

TMC joint workspace was computed from data collected during the multi-movements described in Table 3. Using the motion path of the distal first metacarpal a spherical surface was created that encompassed all of the data points collected during the entire Max TMC movement or MKI. The Newton method sphere fitting algorithm described by Hicks et al. was used to minimize the distance between the sphere surface and each point in the data set, as well as determine the center and radius of the sphere [42]. Briefly, the Newton method begins with an initial estimate of the sphere surface using a least squares approach which is then refined by calculating an improvement vector. The improvement vector is calculated using Singular Value Decomposition, requiring a Jacobian matrix of nonlinear equations and a vector (F_k) created by evaluating the error function of each data point. This process is repeated until the error difference between sequential iterations is minimized to a set threshold [42]. The effectiveness of the Newton method for determining joint centers has been previously validated in other joints of the body, proving to be a robust solution in the presence of restricted motion and increased marker error [42]. It should be noted that this method only computes one sphere center which lies somewhere between the flex/ext and abd/add of the TMC joint.

Following sphere fitting, each data point of the distal first metacarpal, was projected onto a two-dimensional plane. This two-dimensional plane was the base, or flat surface, of the smallest possible cone centered around the origin of the best fit sphere encompassing all of the data points. The location of the two-dimensional plane was found by translating the plane away from the origin of the sphere until it contacted the data point closest to the origin of the sphere. The projection onto the plane was then done by drawing a line from each data point to the origin of the sphere. The intersection of that line with the plane was the projection of the data point onto the plane (Figure 3, 4). A two-dimensional convex hull was then drawn around the points in the plane. Extra points were then added onto the plane to fill in areas that did not have many sampled data points. This was done by projecting a 21 x 21 grid of equally spaced points onto the two dimensional plane based on the minimum and maximum locations of the actual data points. The extra points that fell within the two dimensional convex hull, were then used in addition to the actual data points, when calculating the volume of the convex hull. The extra points were added to avoid any large flat areas which may have occurred when projecting the actual data points in the plane back onto the best fit sphere. If not done this may have led to an underestimate of the convex hull volume and ultimately the TMC workspace measurement. After the extra points were added the points in the plane were projected back out onto a unit sphere (sphere of radius one) by radial extension from the center of the sphere, resulting in an “augmented set of points on the unit sphere”: the original points plus the extra points. Then a 3D convex hull was drawn around the points on the unit sphere plus the center of the sphere (Figure 5, Figure 6). The volume of this convex hull was determined and the surface area was calculated as the volume times 3, since, for a sphere, area/volume = 3/R, and in this case R=1. Adding the extra points into the data set results in an “augmented 3D convex hull”, however this only results in minimal changes to the TMC workspace measurements and does not affect any statistical measures. The largest change in TMC workspace occurs in the MKI task which only increases by 1.7 percent when adding the extra points into the data set.

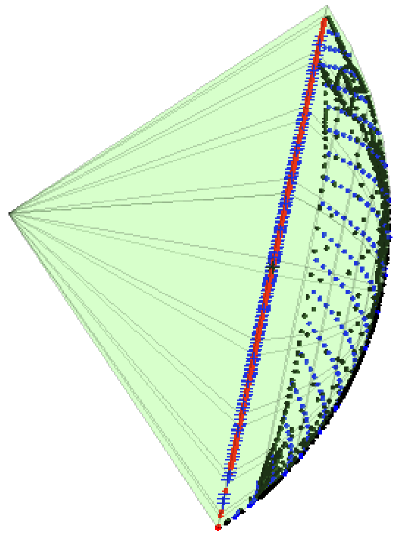

Figure 3: Side View of one part of a best fit sphere. The distal first metacarpal data points are located on the surface of the sphere. They have been projected onto a two-dimensional plane that has been translated away from the origin of the sphere until it contacts the data point located closest to the origin of the sphere.

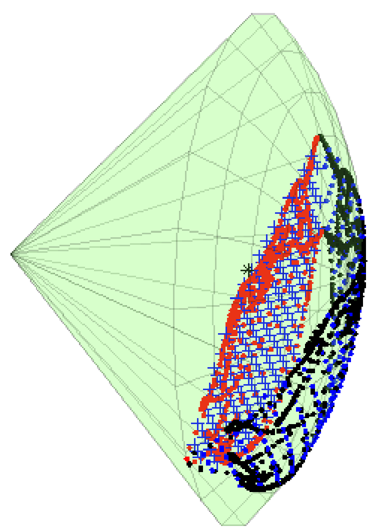

Figure 4: Alternative view of one part of a best fit sphere. The distal first metacarpal data points are located on the surface of the sphere. They have been projected onto a two-dimensional plane that has been translated away from the origin of the sphere until it contacts the data point located closest to the origin of the sphere.

TMC workspace is commonly modeled as the volume of the trajectory formed by the distal first metacarpal [3, 7]. However, to control for differences in thumb metacarpal length between subjects, all thumb metacarpal lengths were normalized to a length of one resulting in a unit sphere with radius equal to one [8]. This allowed the maximal TMC workspace to be modeled as the surface area of the TMC workspace computed from the three dimensional convex hull. Workspace measurements in this study are reported in steradians, also known as radians squared, since they were normalized by metacarpal length. All helical angle, spherical fitting, and convex hull calculations were implemented following data collection using custom software written in LabView (National Instruments, Austin, TX, USA) and Matlab (MathWorks, Natick, MA, USA).

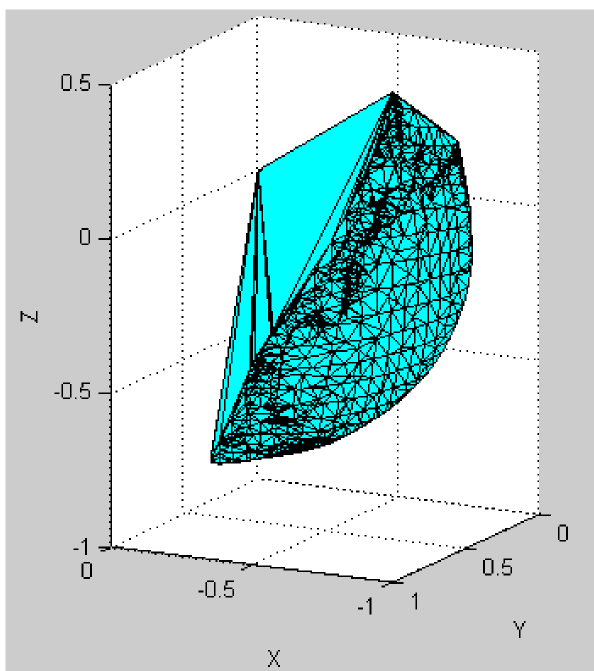

Figure 5 – Augmented Convex Hull during the Max TMC motion (subject 1)

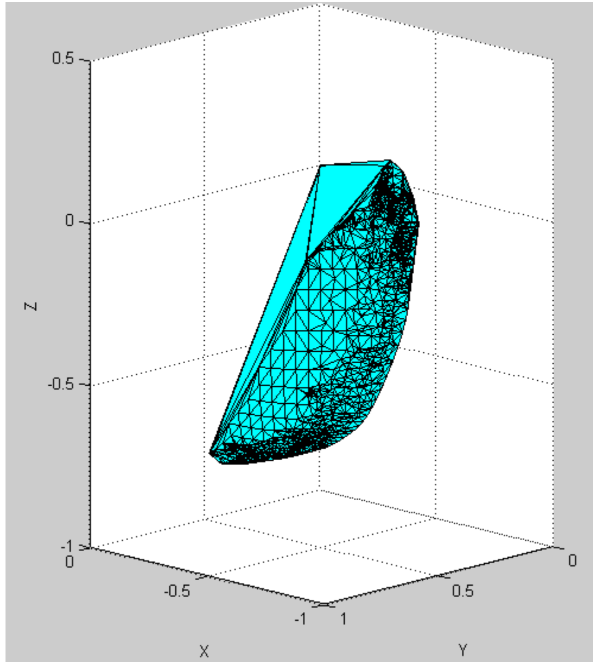

Figure 6 – Augmented Convex Hull during the MKI motion (subject 1)

Statistical Analysis

Prior to data collection a power analysis was completed using G-Power software which identified that 24 subjects were needed to adequately power this study (12 females, 12 males). The power analysis beta level was set to .80, the alpha level was set to .05, and a medium effect size of .30 was used to determine the sample size. Statistical comparisons are separated by hypothesis in the sections below.

Hypothesis 1.1 – Comparisons between the two multi-movements (Max TMC, MKI) were used to determine TMC axis ROM differences, at an alpha level of .05. One 2 X 3 ANOVA (Multi-Movement test method x TMC flex/ext axis, TMC abd/add axis, and TMC workspace) was used to detect these differences.

Hypothesis 1.2 – Comparisons between the two multi-movements (Max TMC, MKI) were used to determine TMC workspace differences, at an alpha level of .05. The same 2 X 3 ANOVA (Multi-Movement test x TMC flex/ext axis, TMC abd/add axis, and TMC workspace) was used to detect these differences. The correlation between the TMC workspace measures from both of the multi-movements was also completed. This was done to see if the MKI workspace could be used as a predictor of maximal TMC workspace.

Hypothesis 2.1 – Comparisons between genders for each planar movement (flex/ext, abd/add) were used to determine the differences in primary TMC axis ROM (i.e. flex/ext axis for the flex/ext motion task), at an alpha level of .05. Two 2 x 2 ANOVAS (Gender x Axis) with repeated measures on the TMC axis were used to detect these differences. Before determining significance a Bonferroni adjustment of .05/2 was used to control for increases in statistical error.

Hypothesis 2.2 – Comparisons between genders for each composite movement (opposition, circumduction) and multi-movement (Max TMC, MKI) were used to determine the ROM differences in both TMC axes, at an alpha level of .05. Four 2 x 2 ANOVAS (Gender x Axis) with repeated measures on the TMC axis were used to detect these differences. Before determining significance a Bonferroni adjustment of .05/4 was used to control for increases in statistical error.

Hypothesis 3.1 – Comparisons between genders for each multi-movement (Max TMC, MKI) were used to determine TMC workspace differences, at an alpha level of .05. One 2 x 2 ANOVA (Gender x Multi-Movement workspace measure) was used to detect these differences.

Chapter 4

RESULTS

Following data collection on 12 male subjects and 12 female subjects, comparisons of flex/ext TMC ROM, abd/add TMC ROM, and TMC workspace were made between each multi-movement test type. Additional comparisons between genders were also made for flex/ext TMC ROM, abd/add TMC ROM, and TMC workspace during each single and multi-movement.

Specific Aim 1

Comparisons between the Max TMC and MKI tasks showed no significant differences in flex/ext TMC ROM (p=.550). However, the abd/add TMC ROM was significantly less during the MKI task than the Max TMC task (p=.038) (Figure 7). The measured TMC workspace was significantly less during the MKI task than the Max TMC task (p=.045) (Figure 8). The Pearson correlation coefficient between the MKI workspace and the Max TMC workspace was .587. The coefficient of determination between these two measures was .345 (Figure 9).

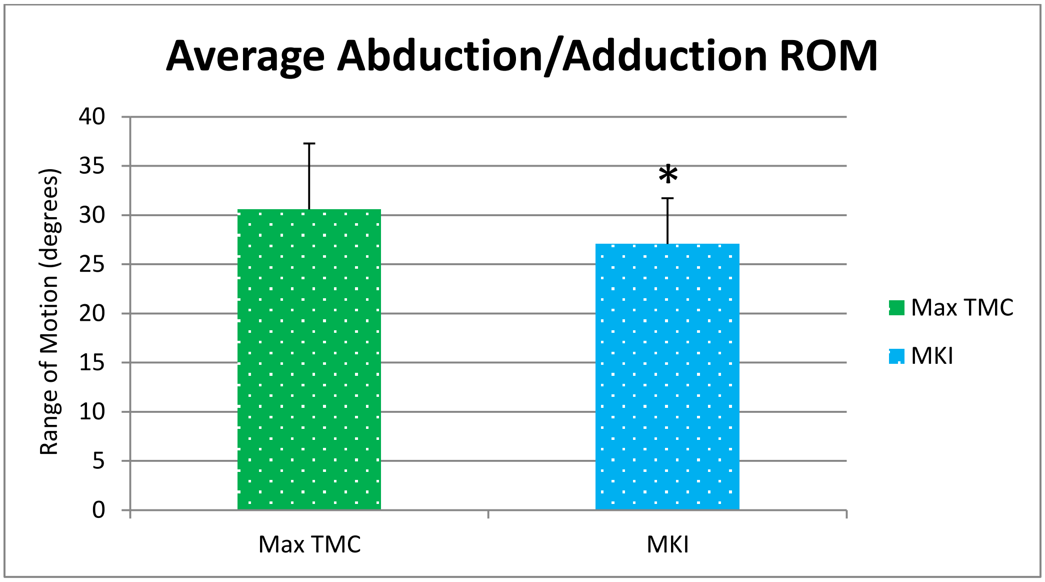

Figure 7 – The average TMC abduction/adduction ROM during the Max TMC and MKI tasks. ROM is reported in degrees as the average. Error bars represent + one standard deviation. The significant difference in ROM between the multi-movement tasks is marked with an asterisk.

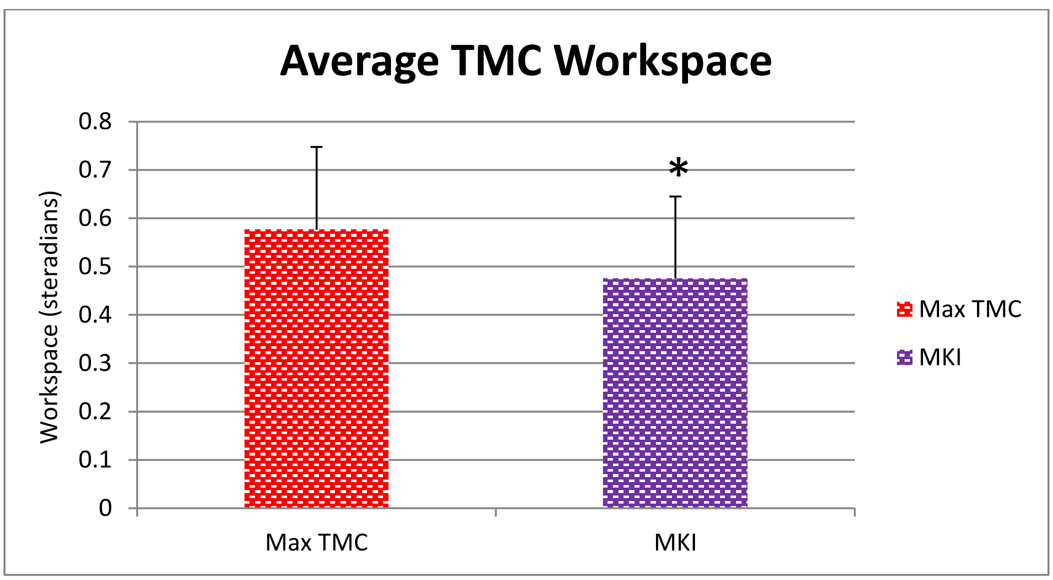

Figure 8 – The average TMC workspace during the Max TMC and MKI tasks. Workspace is reported in steradians (sr), as the average. Error bars represent + one standard deviation. The significant difference in workspace between the multi-movement tasks is marked with an asterisk.

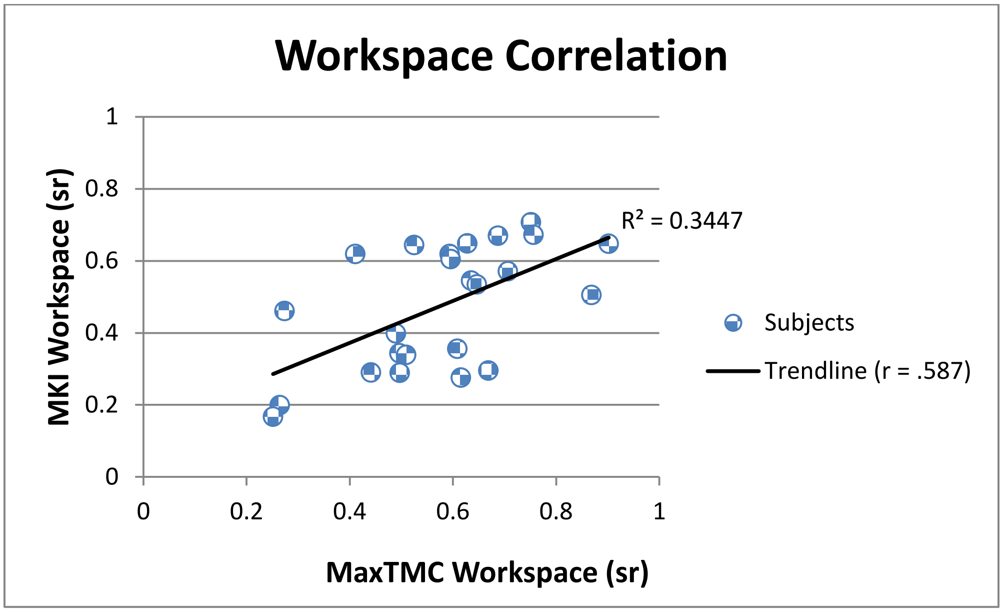

Figure 9 – The correlation between the MKI workspace and Max TMC workspace for each subject. The linear trendline is included in the figure and represents a Pearson correlation coefficient of r = .587 and a coefficient of determination of .345.

Specific Aim 2

The average ROM for each TMC axis has been separated by gender for each thumb motion and is reported in Table 4. Gender comparisons during planar thumb motions showed no significant ROM differences in the primary axes of rotation (p=.320 for flex/ext, p=.275 for abd/add). Comparisons between genders during the composite motions (circumduction, opposition) showed no significant ROM differences in either of the TMC axes. (p = .897 for the flex/ext axis, p = .495 for the abd/add axis during circumduction), (p = .067 for the flex/ext axis, p = .747 for the abd/add axis during opposition). Comparisons between genders for the multi-movement tasks (Max TMC, MKI) showed no significant ROM differences in either of the TMC axes (p = .058 for the flex/ext axis, p = .673 for the abd/add axis during Max TMC), (p=.038 for the flex/ext axis, p=.828 for the abd/add axis during MKI).

Table 4 – Descriptive statistics of each TMC axis separated by gender and thumb motion task. Results are reported in degrees as the average ± one standard deviation. ROM values are reported as absolute values in order to display the total degree of motion.

Motion Task – (Axis)	**Male ROM ◦ (Average ± S.D.)**	**Female ROM ◦ (Average ± S.D.)**
Flexion/Extension – (Flex/Ext)	48.8 ± 10.6 ◦	53.1 ± 10 ◦
Flexion/Extension – (Abd/Add)	21.7 ± 5.8 ◦	18.0 ± 5.7 ◦
Abduction/Adduction – (Flex/Ext)	41.8 ± 11.6 ◦	46.5 ± 10.3 ◦
Abduction/Adduction – (Abd/Add)	23.9 ± 6.8 ◦	27.0 ± 6.6 ◦
Opposition – (Flex/Ext)	53.2 ± 8.7 ◦	60.4 ± 9.7 ◦
Opposition – (Abd/Add)	20.1 ± 5.8 ◦	19.2 ± 6.8 ◦
Circumduction – (Flex/Ext)	49.5 ± 10.9 ◦	48.9 ± 11.9 ◦
Circumduction – (Abd/Add)	31.0 ± 8.5 ◦	29.1 ± 4.5 ◦
Max TMC – (Flex/Ext)	54.7 ± 9.3 ◦	62.7 ± 10.3 ◦
Max TMC – (Abd/Add)	30.0 ± 7.3 ◦	31.2 ± 6.3 ◦
MKI – (Flex/Ext)	56.2 ± 10.1 ◦	64.9 ± 9.3 ◦
MKI – (Abd/Add)	26.8 ± 5.7 ◦	27.3 ± 3.7 ◦

Specific Aim 3

TMC workspaces, separated by gender and multi-movement task are displayed in Figure 10. Gender comparisons during the MKI and Max TMC showed no significant differences in TMC workspace (p=.772 for the MKI, p=.139 for the Max TMC).

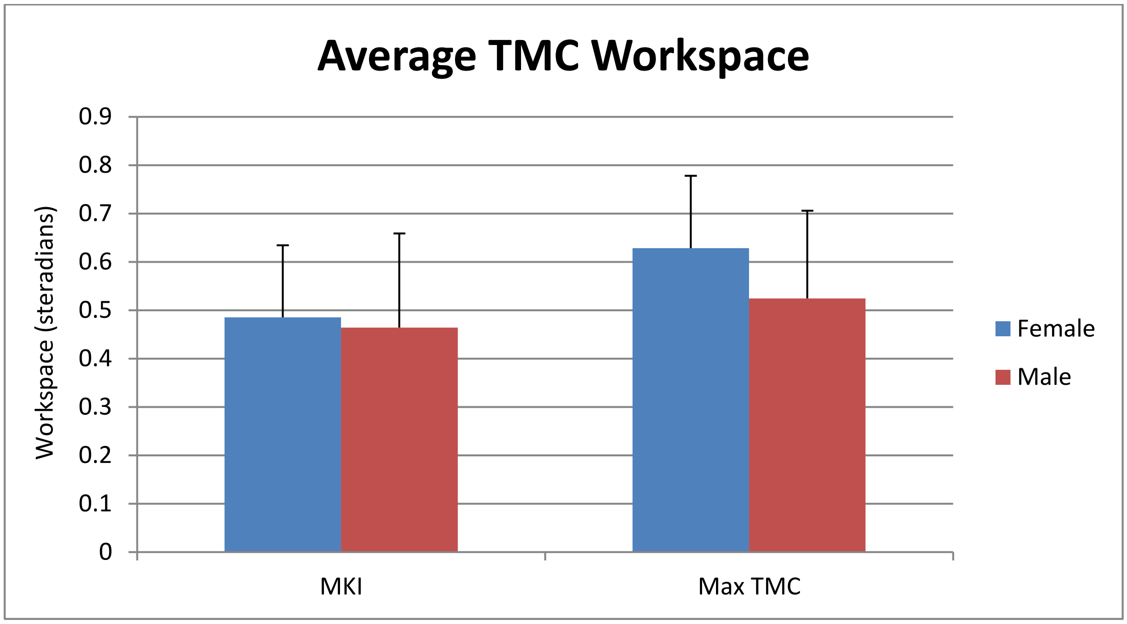

Figure 10 – The average TMC workspace separated by gender and multi-movement task. Results are reported in steradians (sr) as the average. Error bars represent + one standard deviation.

Chapter 5

DISCUSSION

Past studies have analyzed TMC ROM and workspace measurements during simple planar and composite thumb motions. However, none of these studies have compared their results with ROM or workspace measurements obtained during clinical thumb examinations such as the Modified Kapandji Index, which is designed to measure the thumb component of overall thumb mobility [3,7,8,9,10]. In addition, past studies have shown mixed results as to whether ROM and workspace measurements are greater in one gender compared to the other gender [4,6,8,17,18]. The purpose of this study was to determine the ROM and workspace differences at the TMC joint between genders using maximal and clinical ROM measurement techniques. By measuring the ROM of the TMC joint during the thumb opposition portion of the MKI, the MKI was examined as a clinical measure of TMC ROM and workspace by showing the effectiveness of the MKI in measuring maximal TMC ROM and workspace. Results of this study will help to answer the question as to whether one gender displays greater TMC ROM and workspace than the other. Previous studies have identified idiopathic TMC hypermobility as a predisposing factor for the development of TMC OA, especially in the female population [13, 14, 23]. Anatomical variations within the shape and contour of the trapezium are thought to put the TMC joint of the female population in a less stable position leading to increased hypermobility [13]. Even with the knowledge of these anatomical variations definitive answers regarding the gender differences of TMC ROM and workspace are still not well known [4,6,8,17,18]. With the use of three-dimensional motion capture this study examined dynamic in-vivo TMC ROM and workspace to see if there are differences in TMC ROM and workspace between genders. By displaying different TMC ROM and workspace it will have implications in identifying why one gender is more susceptible to developing TMC OA. This would provide an explanation for the greater prevalence of TMC OA that is currently seen in the female population [16, 23].

Previous research has utilized a two degree of freedom joint model to describe motion of the TMC joint in the flex/ext and abd/add axes [1]. Utilizing these pre-existing methods, this study showed an average ROM about the flex/ext and abd/add axes of 59.6 degrees and 28.8 degrees respectively during the multi-movement tasks. During the composite motions (circumduction, opposition) the average ROM about the flex/ext and abd/add axes were 49.2 degrees and 30.1 degrees for circumduction and 56.8 degrees and 19.6 degrees for opposition. These flex/ext ROM results compare favorably with those of past studies using a similar TMC joint model [1,22]. Cerveri et al. showed an average flex/ext ROM of 61 degrees during a series of circumduction and opposition tasks, while this study showed an average ROM of 58.7 degrees during similar movements[1]. Another study, done by Cerveri et al., which estimated TMC motion using several static poses, meant to represent an opposition motion, showed a flex/ext ROM of 50.2 degrees, while this study showed an average ROM of 56.8 degrees during its opposition motion [22].

While the flex/ext ROM results in this study are comparable with past literature, the abd/add ROM results are smaller than those reported previously. Cerveri et al. showed an average abd/add ROM of 41 degrees during a series of circumduction and opposition tasks which is about 10 degrees greater than the 30.1 degrees of abd/add ROM that was seen in this study [1]. Another study done by Cerveri et al., estimating TMC motion using several static poses, meant to represent an opposition motion, showed an abd/add ROM of 40.6 degrees, much greater than the abd/add ROM of 19.6 degrees that was reported during the opposition motion in this study [22]. However, it should be noted that these studies used an opposition task defined by touching the tip of the thumb to the tip of the index finger rather than the base of the palm which may hinder some of the comparisons that can be made between abd/add ROM [1, 22]. Nevertheless, the results obtained in this study agree with past in-vivo and in-vitro research which have shown that the TMC joint displays more flex/ext ROM than abd/add ROM [1, 18, 22, 33].

Workspace measurements in this study were normalized due to variations in metacarpal lengths which may have arisen between individual subjects and subject groups. The average workspace was calculated for each of the multi-movement tasks and was measured to be 0.576 sr for the Max TMC task and 0.475 sr for the MKI task. Kuo et al. showed a slightly larger average normalized workspace value of 0.795 sr during a multi-movement task consisting of maximal thumb flexion/extension, abduction/adduction, and circumduction [8]. These differences can be explained by the methods used to determine TMC workspace. In the study done by Kuo et al, the motion paths of the first metacarpal were fit to a spherical surface using a least squares fitting approach. The TMC workspace was then determined from the data points representing the surface area on one part of the best fit sphere using a surface integral approach [8]. This is different from the current study which uses the Newton Method sphere fitting algorithm to fit the motion path of the first metacarpal to a best fit sphere and then calculates the TMC workspace by determining the convex hull of the data points representing the surface area on one part of the fitted sphere. These different methodological approaches help to explain the differences that exist in average TMC workspace measurements between the current and past literature.

Specific Aim 1

The purpose of this aim was to determine if the TMC ROM and workspace were significantly different between the MKI task and the Max TMC task. Results show that the TMC ROM, specifically the ROM in the abd/add axis was significantly smaller during the MKI task when compared to the Max TMC task (27 degrees during the MKI, 30.6 degrees during the Max TMC). Results also show that the TMC workspace was significantly smaller during the MKI task when compared to the Max TMC task (0.475 sr during the MKI, 0.576 sr during the Max TMC). While the MKI may be an effective clinical test for measuring maximal TMC flexion/extension, results clearly indicate that it lacks the ability to measure the entire ROM about the

TMC abd/add axis. Due to its ineffectiveness in measuring the overall ROM of the TMC joint the MKI test also lacks the ability to measure the entire workspace of the TMC joint (Figure 11, 12). A correlation test of workspace between the MKI and Max TMC tasks help to support this finding. This test displayed only a moderate correlation (r = .587) between the measured workspaces which helps to show that the MKI is not a strong predictor of overall TMC workspace. In the past the MKI has been used as a clinical measure of overall thumb mobility but these results indicate that it lacks the ability to clinically assess the entire ROM and workspace of the thumb [10]. While this test seems like a valuable measure of overall thumb mobility, due to its ability to quickly score individuals on their ability to oppose their thumbs to different locations on the hand, it may be a better measure of overall thumb mobility if done in combination with other tests that display greater ranges of abd/add motion and workspaces [10, 30]. Some of these tests may include a series of gripping or grasping tasks which force the individuals being tested to explore larger amounts of their abd/add ROM and overall TMC workspace [30].

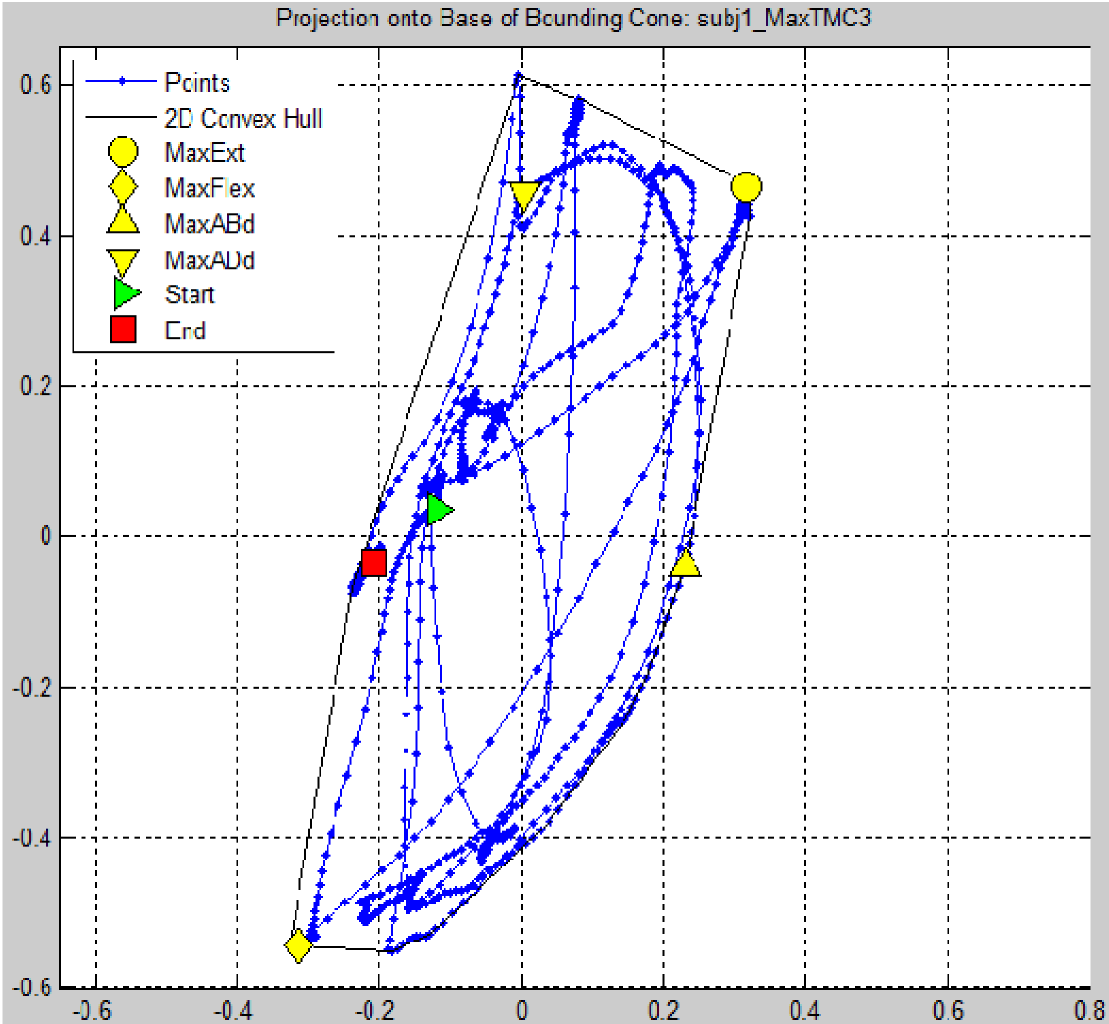

Figure 11 – Two dimensional projection of TMC workspace during the Max TMC task. The start location, end location, maximal flexion location, maximal extension location, maximal abduction location, and maximal adduction location are labeled and identified in the attached legend.

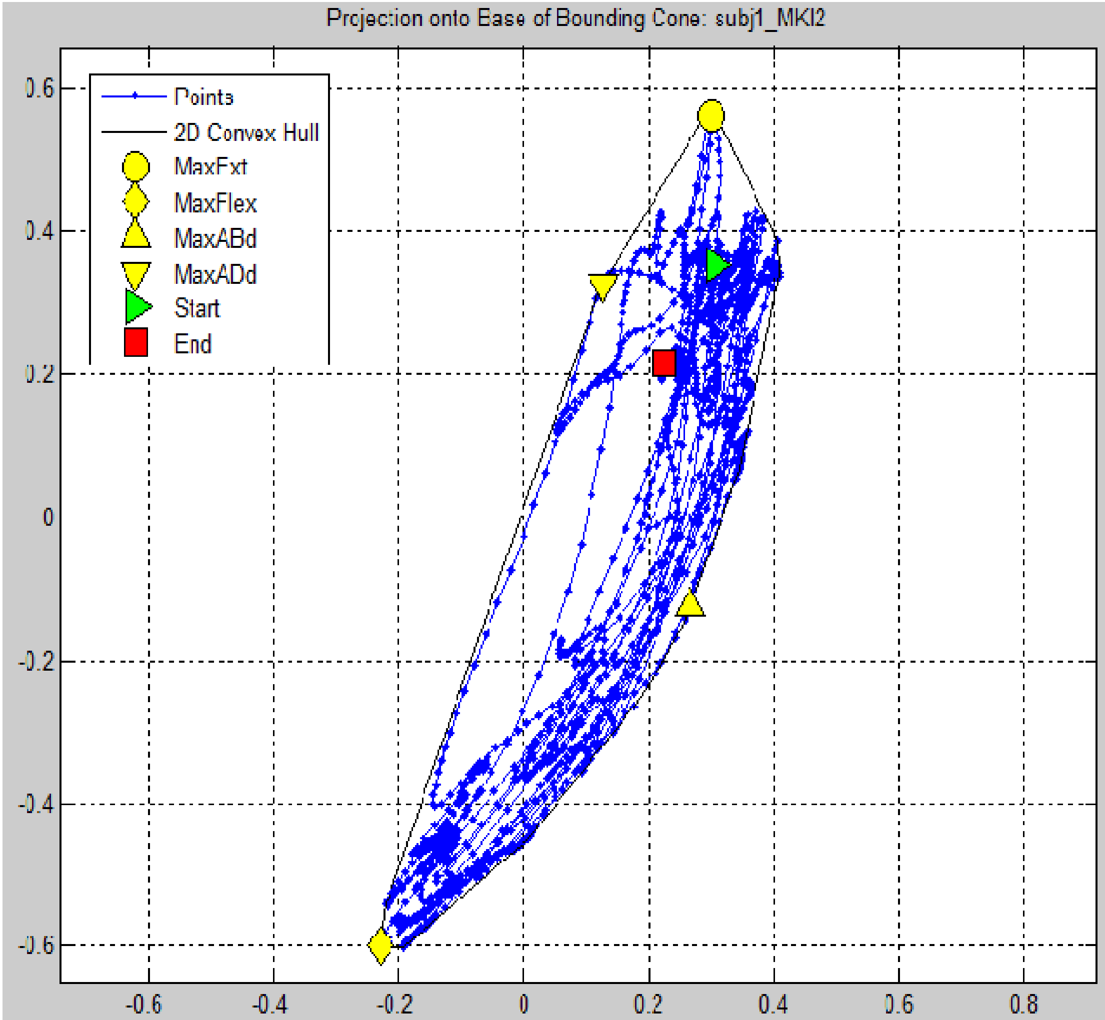

Figure 12 – Two dimensional projection of TMC workspace during the MKI task. The start location, end location, maximal flexion location, maximal extension location, maximal abduction location, and maximal adduction location are labeled and identified in the attached legend.

Specific Aim 2

The purpose of this aim was to determine if the TMC ROM was significantly different between genders using a variety of single movement and multi-movement tasks. Results show that the TMC ROM between genders was not statistically significant in any of the single or multi-movement tasks. These results agree with some of the studies that have been previously cited in the literature. Cooney et al. measured TMC flex/ext and abd/add ROM in 10 males and 9 females during a variety of movements including flexion, extension, abduction, opposition, and grasping. Results from this study indicated no significant differences between genders in either of the TMC axes [18]. Coert et al. measured TMC motion in 12 female and 15 male subjects during a circumduction task and also saw no significant differences between genders [17]. These past studies show non-significant ROM differences between genders which is in agreement with the results seen in this study [17, 18].

A previous study done by Goubier et al. examined the difference in TMC ROM between genders and showed that the abd/add ROM and flex/ext ROM were significantly greater in the female population than the male population, which is opposite to the finding in this current study [4]. However, the ROM results indicated in Goubier et al. do not agree with the ROM results seen in this study or other past literature as the flex/ext ROM was smaller than the abd/add ROM [1,18,22,33]. This is in stark contrast to one of the cost metrics used in a prior optimization approach to find TMC ROM which states that the flex/ext ROM should always be greater than the abd/add ROM , ultimately raising concerns regarding the accuracy of the data presented by Goubier et al. [33].

The ROM results seen in the current study indicate that there is no difference in ROM between males and females, meaning that one gender is not at a greater risk of developing TMC OA due to increased mobility in the TMC joint. However, this does not help to explain why the development of TMC OA is ten times more likely to occur in the female population than the male population [16, 23]. Further research should be done on TMC joint differences between genders to determine if other variables such as TMC joint size or intrinsic/extrinsic tendon excursions could be leading to this discrepancy in TMC OA development.

Specific Aim 3

The purpose of this aim was to determine if the TMC workspace was significantly different between genders using the MKI task and the Max TMC task. Results show that the TMC workspace between genders was not significantly different in either of the multi-movement tasks. Zhang et al. measured the TMC workspace by finding the data points of the first metacarpal within the volume of a 3D cone and concluded that gender did not have an effect on TMC workspace measurements [6]. Kuo et al., mentioned earlier, used a similar process to Zhang et al. to find TMC workspace and when normalized by first metacarpal length, showed no significant differences in TMC workspace between genders [8]. The results from this study are in agreement with those of past literature, and they help to strengthen the finding that there are no significant ROM or workspace differences between genders in the TMC joint [6, 8]. Again, this does not help to explain why the development of TMC OA is so much higher in females than in males, which raises further research questions about the cause of this gender discrepancy.

Limitation

By not controlling for menstrual cycle changes in the female subjects, some may argue that small amounts of error could have been generated in the female ROM and workspace measurements. This is due to the fact that females have been shown to display different amounts of laxity at different stages of their menstrual cycle [43]. However, since the stages of the menstrual cycle were not controlled or recorded, it can be assumed that our female subject population represented a range of stages. Since the measurements were averaged for the entire female subject population, different menstrual cycle stages should not have an effect on the final measurements. This small limitation does not deter from fulfilling the overall aims of this thesis; to determine whether the TMC ROM and workspace between genders and ROM measurement technique are significantly different.

Future Work

The abundance of upper extremity disorders has become an important occupational health issue across all industry sectors accounting for up to 33 percent of lost work day injuries in the manufacturing industry alone [5,39]. Since TMC OA has been shown to be one of the most common musculoskeletal disorders in the upper extremity it becomes evident that there is a need to accurately model human thumb motion to determine its biomechanical function in everyday life [11,40]. Future research should aim to continue and expand upon this research study by developing an accurate musculoskeletal model aimed at analyzing the mobility, loading capacity, and functional capacity of the human thumb. An accurate musculoskeletal thumb model will help to determine the role of thumb motion and loading in the onset and progression of OA and other thumb related pathologies. It will also provide surgeons and clinicians with a valuable tool that can be used to optimize pre-surgical planning and quantifiably evaluate the effectiveness of different treatment interventions. Results of this study along with future research combining thumb kinematics, thumb kinetics, and musculoskeletal modeling will accelerate the development of an accurate musculoskeletal thumb model, ultimately increasing the functional ability and quality of life in patients with thumb pathologies.

Conclusions

This thesis utilized an anatomically correct TMC joint model to make TMC ROM and workspace comparisons between genders and different ROM measurement techniques. Results from this study have shown that there are no significant differences between genders regarding TMC ROM or workspace. These results indicate that increased mobility is not a viable explanation for the increased likelihood of developing TMC OA in the female population, which raises further research questions aimed at determining the TMC joint differences between genders which may explain the discrepancy in TMC OA development. Results have also determined that the abd/add TMC ROM and workspace are significantly smaller during the clinical MKI test when compared to a test of Maximal TMC ROM. This indicates that the clinical MKI test is ineffective in measuring the entire ROM and workspace of the thumb and may need to be done in unison with other tests to ensure that the patient is exploring a greater amount of their available TMC abd/add ROM and workspace. These results are important to both clinicians and patients as it may help to improve on the process of clinically measuring and evaluating thumb ROM and function in injured and pathological populations. While this research has proven beneficial in determining kinematic differences between healthy populations, future research should focus on the development of an accurate musculoskeletal model of the human thumb with the ability of assessing both kinematic and kinetic parameters. This would prove to be a valuable tool that could be used to track the onset and progression of thumb related pathologies as well as make comparisons between different subject populations, such as individuals with healthy TMC joints and individuals with osteoarthritic TMC joints. This future thumb model would also be a monumental tool which could be used by surgeons and clinicians to optimize pre-surgical planning and assess different treatment outcomes at an individual patient level.

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Appendix A

TMC RANGE OF MOTION AND WORKSPACE DATA

Test Type	Flexion Axis	Abduction Axis	Workspace
MaxTMC	58.974	36.74	0.609
MaxTMC	49.625	26.483	0.489666667
MaxTMC	57.812	35.096	0.6358
MaxTMC	62.072	38.743	0.524833333
MaxTMC	74.773	43.853	0.751766667
MaxTMC	55.802	24.216	0.869066667
MaxTMC	46.915	21.318	0.594
MaxTMC	43.586	31.145	0.595833333
MaxTMC	49.537	26.404	0.902166667
MaxTMC	47.592	28.489	0.410766667
MaxTMC	64.206	27.663	0.2739
MaxTMC	45.646	19.811	0.7071
MaxTMC	64.367	29.288	0.6155
MaxTMC	64.998	34.062	0.756566667
MaxTMC	71.847	32.03	0.6279
MaxTMC	44.675	16.829	0.497333333
MaxTMC	58.395	33.058	0.496733333
MaxTMC	57.754	33.16	0.441633333
MaxTMC	81.385	25.408	0.687533333
MaxTMC	69.238	24.372	0.669
MaxTMC	59.97	38.823	0.647033333
MaxTMC	50.071	34.906	0.509533333
MaxTMC	73.576	34.962	0.2645
MaxTMC	56.523	37.325	0.251466667
MKI	64.36	28.081	0.355833333
MKI	50.831	27.704	0.3979
MKI	55.971	30.186	0.54515
MKI	61.435	34.489	0.643366667
MKI	80.059	38.353	0.706566667
MKI	55.749	21.658	0.5051
MKI	48.313	19.972	0.618766667

MKI	46.318	25.091	0.604133333
MKI	51.648	27.713	0.646866667
MKI	55.558	25.751	0.619133333
MKI	62.162	23.785	0.4609
MKI	41.568	19.194	0.5709
MKI	67.944	24.638	0.2751
MKI	67.92	27.551	0.672366667
MKI	72.735	26.255	0.648333333
MKI	43.261	20.781	0.2885
MKI	72.531	29.957	0.342866667
MKI	64.034	20.881	0.289766667
MKI	78.406	28.126	0.669766667
MKI	62.753	29.117	0.294733333
MKI	68.991	28.828	0.533866667
MKI	53.163	28.017	0.3384
MKI	61.694	29.621	0.198866667
MKI	65.687	33.348	0.167166667

Appendix B

TMC RANGE OF MOTION DATA SEPARATED BY GENDER

	Abduction		Circumduction		Flexion		MaxTMC		MKI		Opposition	
Gender	Abd	Flex	Abd	Flex	Abd	Flex	Abd	Flex	Abd	Flex	Abd	Flex
Male	27.43	54.1	32.054	60.507	21.628	56.1	36.74	58.97	28.1	64.4	22.75	57.937
Male	15.85	39.4	25.436	44.939	31.938	40	26.48	49.63	27.7	50.8	17.91	50.771
Male	30.36	47.4	34.544	55.182	26.446	39.3	35.1	57.81	30.2	56	11.41	50.867
Male	37.27	40.6	44.309	55.813	18.362	58.3	38.74	62.07	34.5	61.4	28.37	57.231
Male	28.52	54.4	46.179	71.127	21.272	71.1	43.85	74.77	38.4	80.1	22.98	74.038
Male	18.6	43.5	25.275	56.95	21.092	53.9	24.22	55.8	21.7	55.7	17.08	55.986
Male	27.58	54.5	22.721	47.547	25.433	42.1	21.32	46.92	20	48.3	25.89	49.211
Male	23.54	39.5	30.994	37.753	20.59	37.9	31.15	43.59	25.1	46.3	23.35	44.75
Male	20.49	31.7	38.243	36.54	16.923	37.4	26.4	49.54	27.7	51.6	14.65	48.093
Male	15.3	31.9	28.856	48.169	26.721	46.5	28.49	47.59	25.8	55.6	27.62	45.554
Male	25.46	49.1	19.39	44.954	20.944	58.2	27.66	64.21	23.8	62.2	15.57	60.971
Male	16.08	15.2	24.454	34.306	8.868	44.8	19.81	45.65	19.2	41.6	13.37	42.571
Female	21.77	53.7	28.894	60.053	12.291	60.9	29.29	64.37	24.6	67.9	21.56	57.501
Female	29.34	45.7	31.397	32.856	13.35	62.3	34.06	65	27.6	67.9	15.43	70.417
Female	31.15	44	32.577	62.672	21.216	59.7	32.03	71.85	26.3	72.7	16.12	69.927
Female	18.63	31.7	20.127	38.983	7.947	39.2	16.83	44.68	20.8	43.3	10.8	42.466
Female	32.34	54.1	31.904	61.099	19.432	55.4	33.06	58.4	30	72.5	13.18	56.074
Female	28.74	35.5	33.113	37.342	12.06	50.9	33.16	57.75	20.9	64	16.41	60.063
Female	13.86	52.6	26.455	70.698	21.952	68.7	25.41	81.39	28.1	78.4	14.6	77.733
Female	22.67	43.7	23.194	46.526	18.827	48	24.37	69.24	29.1	62.8	19.2	54.038
Female	33.19	45.8	26.007	43.733	16.556	41.8	38.82	59.97	28.8	69	27.71	64.057
Female	29.41	31.4	28.441	39.456	20.851	44.5	34.91	50.07	28	53.2	15.02	52.08
Female	25.66	66.2	31.928	44.908	24.493	63.6	34.96	73.58	29.6	61.7	29.9	66.383
Female	36.48	53	35.41	48.174	26.95	42	37.33	56.52	33.3	65.7	30.94	54.467

Appendix C

TMC WORKSPACE DATA SEPARATED BY GENDER

Gender	Age	MaxTMC_Area4	MKI_Area4
Male	32	0.489666667	0.3979
Male	31	0.524833333	0.6433667
Male	25	0.751766667	0.7065667
Male	31	0.594	0.6187667
Male	21	0.595833333	0.6041333
Male	23	0.902166667	0.6468667
Male	25	0.410766667	0.6191333
Male	24	0.497333333	0.2885
Male	26	0.496733333	0.3428667
Male	25	0.509533333	0.3384
Male	22	0.2645	0.1988667
Male	23	0.251466667	0.1671667
Female	24	0.609	0.3558333
Female	22	0.6358	0.54515
Female	28	0.869066667	0.5051
Female	24	0.2739	0.4609
Female	22	0.7071	0.5709
Female	24	0.6155	0.2751
Female	27	0.756566667	0.6723667
Female	31	0.6279	0.6483333
Female	30	0.441633333	0.2897667
Female	23	0.687533333	0.6697667
Female	19	0.669	0.2947333
Female	27	0.647033333	0.5338667

Appendix D

IRB APPROVAL LETTER

UNIVERSITY OF DELAWARE

RESEARCH OFFICE

210 Hullihen Hall
University of Delaware
Newark, Delaware 19716-1551
Ph: 302/831-2136
Fax: 302/831-2828

DATE:	November 20, 2012
TO:	Robert Hulbert
FROM:	University of Delaware IRB
STUDY TITLE:	[399882-1] Determining Kinematic Differences between Genders at the Trapeziometacarpal Joint
SUBMISSION TYPE:	New Project
ACTION:	APPROVED
APPROVAL DATE:	November 20, 2012
EXPIRATION DATE:	November 19, 2013
REVIEW TYPE:	Expedited Review
REVIEW CATEGORY:	Expedited review category # 4

Thank you for your submission of New Project materials for this research study. The University of Delaware IRB has APPROVED your submission. This approval is based on an appropriate risk/benefit ratio and a study design wherein the risks have been minimized. All research must be conducted in accordance with this approved submission.

This submission has received Expedited Review based on the applicable federal regulation.

Please remember that informed consent is a process beginning with a description of the study and insurance of participant understanding followed by a signed consent form. Informed consent must continue throughout the study via a dialogue between the researcher and research participant. Federal regulations require each participant receive a copy of the signed consent document.

Please note that any revision to previously approved materials must be approved by this office prior to initiation. Please use the appropriate revision forms for this procedure.

All SERIOUS and UNEXPECTED adverse events must be reported to this office. Please use the appropriate adverse event forms for this procedure. All sponsor reporting requirements should also be followed.

Please report all NON-COMPLIANCE issues or COMPLAINTS regarding this study to this office.

Please note that all research records must be retained for a minimum of three years.

Based on the risks, this project requires Continuing Review by this office on an annual basis. Please use the appropriate renewal forms for this procedure.

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If you have any questions, please contact Jody-Lynn Berg at (302) 831-1119 or jberg@udel.edu. Please include your study title and reference number in all correspondence with this office.