USING BIOMECHANICS TO UNDERSTAND THE EFFECTS OF AGING AND EXERCISE ON OSTEOARTHRITIC AND HEALTHY THUMBS

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ABSTRACT

USING BIOMECHANICS TO UNDERSTAND THE EFFECTS OF AGING AND EXERCISE ON OSTEOARTHRITIC AND HEALTHY THUMBS

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Thumb carpometacarpal (CMC) motion, motion between the thumb and the wrist, is primarily responsible for our ability to grasp objects, open jars, and makes up 50% of arm function[1,2]. To improve hand function and the quality of life in persons with CMC osteoarthritis (OA), it is critical that we improve our ability to monitor changes in thumb function. The first step is to augment our methods to quantify the functional losses and used these methods to identify effects of treatment.

The overarching goal of this work was to quantify the differences in motion and force abilities of persons with and without thumb CMC OA, and to measure the ability of hand stretching and strengthening exercises to increase thumb function in persons with CMC OA. Initial motion and force datasets were collected from young healthy persons (n = 23), older healthy persons (n = 11), and older persons with diagnosed CMC OA (n = 24). Following collection of initial datasets, study participants were given daily hand stretching exercises. After two weeks, motion and force datasets were collected a second time. Participants then were given daily strengthening hand exercises to be completed in addition to the daily stretching exercises. Following four weeks of combined stretching and strengthening exercises, participant motion and force datasets were collected a final time.

For this work, there were three aims:

Aim 1 was 1) to develop a method to measure isolated thumb forces in multiple directions, 2) to demonstrate this method on three populations, young healthy, older healthy, and older

participants with OA of the CMC joint, and 3) to identify the effects of short-term hand exercises on thumb force production and grip strength in these three groups. Results showed that both thumb and grip forces improved in young healthy females, older healthy females and males, and older osteoarthritic females and males. In contrast, young healthy males increased their grip forces following exercise, but not their thumb strength. This suggests that thumb and strength forces are not interchangeable, and that thumb forces should be collected in a clinical setting to better track the effects of intervention (exercise, surgery, etc.) on thumb function.

Aim 2 was 1) to determine differences in thumb motions across three groups of participants (i.e., young healthy, older healthy and those with CMC OA) and 2) to determine if multi-planar motions provided additional movement information in comparison to standard planar measures. Both standard thumb ranges of motion typically collected in clinic and new multi-planar motion datasets were obtained from all participants. Results indicated that motion capture was capable of detecting changes in CMC mobility due to the effects of aging and OA pathophysiology that were not detected using standard approaches, and use of multi-planar measurements have the potential to identify changes that are indicators of early stages of OA.

Aim 3 was to identify changes in CMC motions as a result of a six-week exercise regimen on CMC OA participants as determined through two approaches 1) standard goniometry measures and 2) complex movements measured through the use of a motion capture system. We found that six weeks of exercise were sufficient to improve standard CMC ranges of motion using goniometry, and produce trends of improvement using motion capture.

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KEY TO ABBREVIATIONS

3D	three dimensional
CMC	carpometacarpal
DIP	distal interphalangeal
FIHOA	functional index of hand osteoarthritis
IP	interphalangeal
LRTI	ligament reconstruction tendon interposition
MCP	metacarpophalangeal
OA	osteoarthritis
OH	older healthy
PCA	principal component analysis
PIP	proximal interphalangeal
ROM	range of motion
VAS	visual analogue scale
YH	young healthy

CHAPTER 1: INTRODUCTION

1.1 Overview

Thumb carpometacarpal (CMC) motion, motion between the thumb and the wrist, sets us apart from other species. Although humans are not the only primates capable of opposition, which is the ability to touch the thumb to another finger on the same hand, they are the only species capable of producing a pinch grasp[3]. Although the thumb CMC joint is relatively small, CMC joint motion is primarily responsible for our ability to grasp objects, open jars, and is necessary for nearly 50% of arm function[1,2].

When CMC motion and strength becomes impaired, as is the case in persons with CMC osteoarthritis (OA), hand and arm function is significantly affected. CMC OA reduces hand function abilities and impedes completion of daily tasks like buttoning shirts and unlocking doors. In extreme cases, CMC OA can impair a person's ability to care for themselves, resulting in 24 hour care[4]. To improve hand function and the quality of life in persons with CMC OA, it is critical that we improve our ability to monitor changes in thumb function. The first step is to augment our methods to quantify the functional losses and used these methods to identify effects of treatment.

The overarching goal of this work was to quantify the differences in motion and force abilities of persons with and without thumb CMC OA, and to measure the ability of hand stretching and strengthening exercises to increase thumb function in persons with CMC OA.

For this work, initial motion and force datasets were collected from young healthy persons (n = 23), older healthy persons (n = 11), and older persons with diagnosed CMC OA (n = 24). Following collection of initial datasets, study participants were given daily hand stretching exercises. After two weeks, motion and force datasets were collected a second time. Participants then were given daily strengthening hand exercises to be completed in addition to the daily stretching exercises. Following four weeks of combined stretching and strengthening exercises, participant motion and force datasets were collected a final time.

This work has been divided into five chapters with chapters two-four written in the form of a publication (chapter two is under review):

Chapter one is a literature review that discusses some basic anatomy of the hand, CMC joint function, osteoarthritis presentation and statistics, clinical treatment and outcomes, and knowledge gaps that must be addressed to further our understanding of CMC OA development and successful treatment.

Chapter two describes the development of new methods for thumb *force* data collection, and force data prior to and following six weeks of hand exercises. The goals of this study were to 1) develop a method to measure isolated thumb forces in multiple directions, 2) demonstrate this method on three populations, young healthy, older healthy, and older participants with OA of the CMC joint, and 3) identify the effects of short-term hand exercises on thumb force production and grip strength in these three groups. Datasets were collected at three time points: week 0 (prior to intervention), week two (following two weeks of stretching exercises) and week six (following an additional four weeks of stretching and strengthening exercises).

Results showed that both thumb and grip forces improved in young healthy females, older healthy females and males, and older osteoarthritic females and males. In contrast, young healthy males increased their grip forces following exercise, but not their thumb strength. This suggests that thumb and strength forces are not interchangeable, and that thumb forces should be collected in a clinical setting to better track the effects of intervention (exercise, surgery, etc.) on thumb function.

Chapter three focuses on *motion* evaluation and testing prior to exercise intervention in the same participants described in chapter two. The goals of this research were 1) to determine differences in thumb motions across three groups of participants (i.e., young healthy, older healthy and those with CMC OA) and 2) to determine if multi-planar motions provided additional movement information in comparison to standard planar measures. Both standard thumb ranges of motion typically collected in clinic and new multi-planar motion datasets were obtained from all participants. Results indicated that motion capture was capable of detecting changes in CMC mobility due to the effects of aging and OA pathophysiology that were not detected using standard approaches, and use of multi-planar measurements have the potential to identify changes that are indicators of early stages of OA.

Chapter four compared pre- and post-exercise motion datasets (i.e., goniometry and motion data) in the CMC OA participants. All participants completed the same stretching and strengthening exercises over six weeks with testing occurring at week zero, week two, and week six. The goal of this research was to identify changes in CMC motions as a result of a six-week exercise regimen. These changes were determined through two approaches 1) standard goniometry measures and 2) complex movements measured through the use of a motion capture system. We found that six weeks of exercise were sufficient to improve standard CMC ranges of motion using goniometry, and produce trends of improvement using motion capture.

Chapter five contains the overall conclusions of the entire body of work and suggestions for future work.

1.2 Demographics

Osteoarthritis (OA) is characterized by articular cartilage wear and damage to the underlying bone. Although considered a disease of aging, long-term joint use alone is not sufficient to cause

OA onset[5,6]. Incidence and prevalence increase with age, and women are more likely to be affected, primarily due to hormone differences between the sexes[6–14]. Persons with OA also have higher medical costs, increased risk of hospital admittance and re-admittance, and more missed work than persons without OA[15–18]. OA can affect any joint, but most commonly involves the hips, knees, and the hands.

Hand OA, and more specifically OA of the carpometacarpal (CMC) joint located at the base of the thumb, has a significant impact on hand function and quality of life[1,2,4,11,19–24]. The goal of this chapter is to summarize and interpret the currently available research on OA of the hand and thumb CMC joint. This chapter will encompass thumb CMC joint mechanics, measures of hand function, OA risk factors, and gaps of knowledge in these areas.

Radiographic changes associated with hand OA, or changes that are visible on radiographic examination such as joint space narrowing, the presence of bone spurs, and subchrondral sclerosis, are present in over 40% of American adults[25,26]. However, evidence of OA on radiographs is found in populations worldwide, with the prevalence in some populations approaching 80%[25,27,28]. In the U.S., hand OA presents symptomatically in seven to 22% of the population; in other countries such as Israel, symptomatic OA affects over 75% of the aging population[7,25]. Genetics are believed to be a strong component of OA incidence in countries like Israel; for example, Ashkenazi Jews had three times the rate of OA as Sepharadi Jews in that study[29]. The thumb CMC joint is one of the most common joints affected by OA with 21% of the population exhibiting OA changes on radiographs[30–32]. The population most affected by thumb CMC OA is post-menopausal women where two thirds to one-half with CMC OA report symptoms[33]. Additionally, as the aging population continues to increase, the number of patients affected by thumb CMC OA also increases[34].

Loss of hand function can lead to loss of self-reliance and independent living[4]. This is because 50% of upper limb function comes from the thumb, primarily from the CMC joint. OA of the CMC joint is associated with poor range of motion (ROM), reduced ability to complete activities of daily living, and difficulty performing tasks like opening jars[1,2,4,11,19–24]. However, few have investigated the kinematic and biomechanical changes that alter hand function in these persons.

1.3 Ligaments and Muscles

Ligaments play a crucial role in CMC joint stability. Multiple ligaments and muscles have been identified as key supports to prevent dorsoradial subluxation of the first metacarpal[35–38]. The ligament structure itself is quite complex; even the number of ligaments reported to attach to the CMC joint is conflicting[39,40]. It is generally agreed that the anterior oblique ligament, the deep anterior oblique ligament, the posterior oblique ligament, the dorsoradial ligament, the intermetacarpal ligament, the ulnar collateral ligament, and the radial collateral ligament are all important for CMC joint stability[35,39,41–43]. Of these, both the anterior oblique ligament and the dorsoradial ligament have consistently been identified as the primary stabilizers of the CMC joint[35,39,42,44].

The thumb CMC joint relies heavily on peri-CMC joint muscles to produce joint motion and maintain joint stability (Figure 1-1). The abductor pollicis longus and abductor pollicis brevis, located on the dorsoradial side of the thumb, move the thumb during radial and palmar abduction. The opponens pollicis, located radial to the abductor pollicis brevis, aids thumb movement into palmar abduction and opposition. On the ulnar side of the thumb, the adductor pollicis moves the thumb into radial and palmar adduction. Wrist stabilizers, both extrinsic flexors and extensors, are also important for CMC joint and thumb function. Both the first dorsal interosseous and the opponens pollicis have been shown to protect against subluxation of the first metacarpal[37,38]. In short, peri-CMC muscles help maintain healthy joint alignment and preserve joint motion.

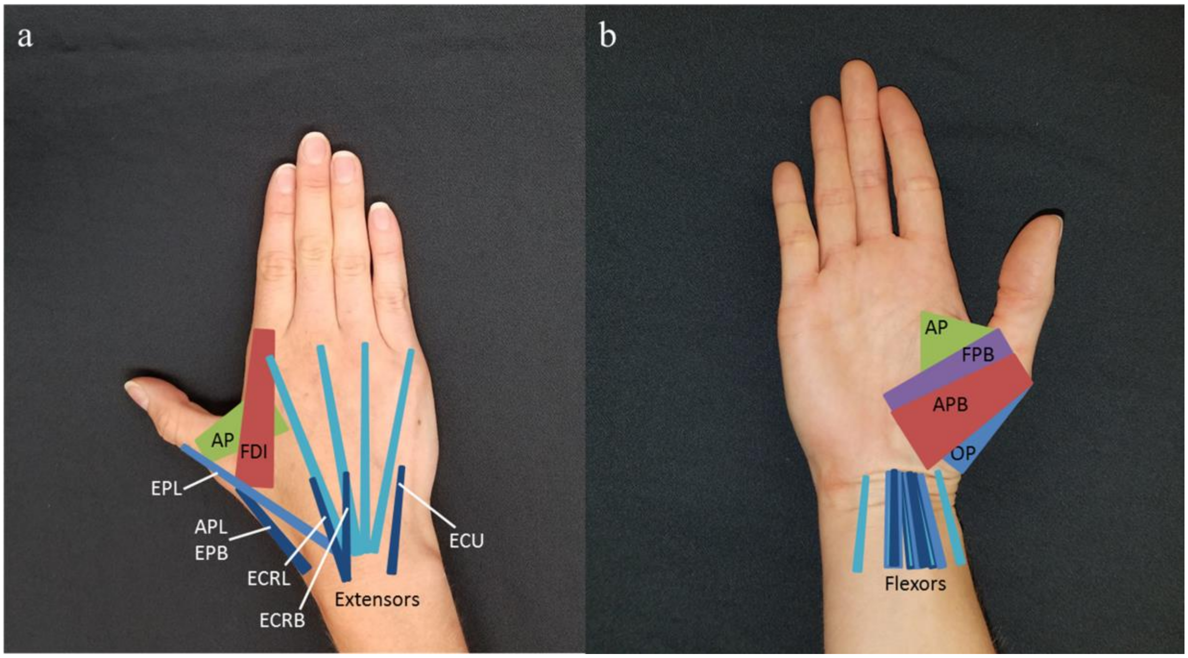

Figure 1-1: Muscles and tendons that play a role in thumb motion and stability.
Muscles and tendons are shown from a) dorsal and b) palmar views of the hand. Abbreviations are as follows: adductor pollicis (AP), abductor pollicis brevis (APB), abductor pollicis longus (APL), extensor carpi radialis brevis (ECRB), extensor carpi radialis longus (ECRL), extensor capri ulnaris (ECU), extensor pollicis brevis (EPB), extensor pollicis longus (EPL), first dorsal interosseous (FDI), flexor pollicis brevis (FPB), and opponens pollicis (OP). ECRB, ECRL, ECU, and EPLshown in panel a are also considered extensor tendons.

1.4 CMC Joint Mechanics

The bones of the hand include the metacarpals, proximal phalanges, middle phalanges, and distal phalanges (Figure 1-2). Although OA can affect the joints between any of these bones, hand OA most often affects the thumb CMC joint, the proximal interphalangeal (PIP) joints, and the distal interphalangeal (DIP) joints[45].

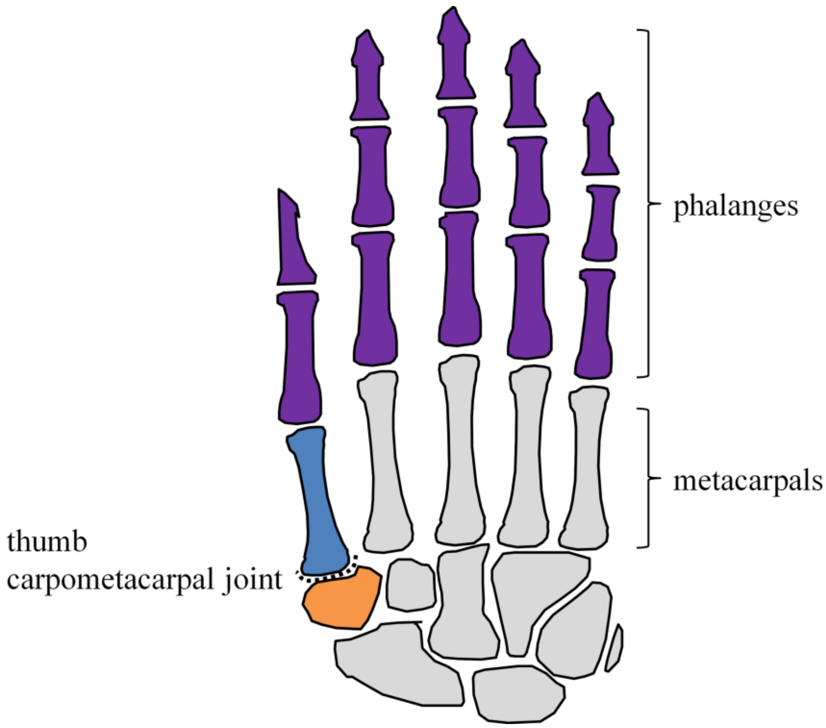

Figure 1-2: Dorsal view of hand anatomy.
The thumb carpometacarpal joint is shown as the dashed line between the first metacarpal (shaded blue) and trapezium (shaded orange). Interphalangeal joints are located between the phalanges (shaded purple) and metacarpophalangeal joints are located between the metacarpal and the phalanges.

The CMC joint has the ability to move in four directions: palmar abduction, palmar adduction, radial abduction (also known as flexion), and radial adduction (extension; Figure 1-3). When these motions are coupled, rotation occurs allowing for opposition and reposition[46].

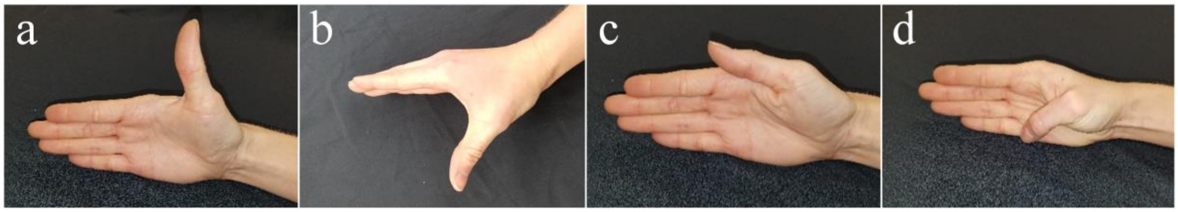

Figure 1-3: Directions of thumb movement.
a) radial abduction, b) palmar abduction, c) radial and palmar adduction, and d) opposition.

In opposition, the thumb rotates about its long axis so the palmar surface of the thumb can touch the palmar surface of other fingers. In retroposition, the thumb rotates away from the other fingers, extending toward the dorsoradial side of the arm. The average ROM is 40-70° in palmar adduction-abduction, 40-63° in radial adduction-abduction, and 17-31° in opposition-retroposition[47–50]. CMC joint motion is necessary to perform various grips. During key pinch, the CMC joint moves in a palmar direction by palmar abduction and opposition, and while grasping a jar, the CMC joint moves in a distal ulnar palmar direction combing radial and palmar abduction[51].

The CMC joint's ROM comes from its unique structure. The CMC joint is one of only three saddle joints found in the body. The first metacarpal and trapezium have concavity differences between their dorsovolar and radioulnar sides. Specifically, the metacarpal is concave in the dorsovolar direction and convex in the radioulnar direction, while the convex and concave shapes are found in opposite planes of the trapezium[13,39,52]. Multiple contact planes allow the metacarpal to move over the trapezium, producing a loose, unstable fit between the bones[52–55]. Thus, the large ROM of the CMC joint comes at a price—reduced joint stability.

1.5 Measures of Hand Function

Current clinical measures are not sufficient to detect the multi-directional motion and force deficits that alter thumb function in early CMC OA. While it is clear that motion and force play a critical role in OA pathophysiology, standard clinical measures lack the specificity to detect them[1,5,55–58]. This led to the development of a multitude of prescription philosophies, prescribed exercise regimens, patient outcomes, and lack of best practice recommendations[59–61]. Further quantification of the improvements associated with treatment interventions is necessary to shape treatment protocols, change therapy prescription, and improve decision-making, thereby reducing treatment costs[62,63].

In a clinical setting, goniometers are typically used to measure joint ROM (Figure 1-4). Goniometers have a planar design that measures ROM in a single axis, but they cannot measure the full three-dimensional motion of the thumb CMC joint[8,42,64]. Goniometers have low accuracy and poor inter-rater reliability[65–67].

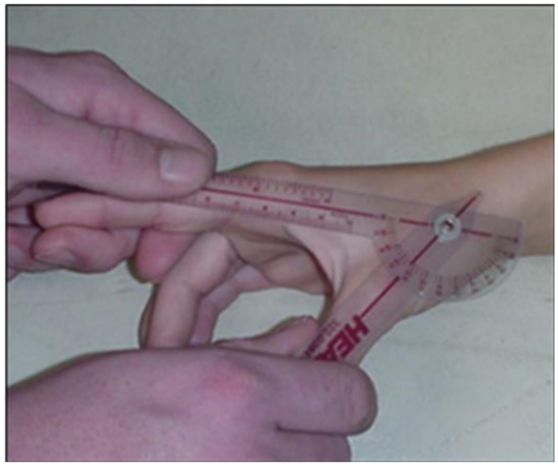

Figure 1-4: Goniometer example.
An example of a goniometer used to measure range of motion of the joints in the hand.

Hand strength is typically measured using a hand grip dynamometer. Although dynamometers measure total hand strength, they cannot measure the strength contributions of individual digits. Currently, no device can measure individual digit or joint specific strength in multiple directions. The lack of such a device makes it difficult to track the effect of therapy in joint specific pathologies like CMC OA.

Additional measures are necessary to identify the motion and force changes associated with thumb CMC OA. Motion capture technology can measure ROM and joint alignment in three-dimensions with high levels of accuracy, making it a superior method to measure thumb CMC motion[65,68,69]. Unlike grip dynamometers, a multi-axis load cell with an appropriately designed interface, can measure both force magnitudes and directions of the isolated thumb. When used concurrently, motion capture and load cell technologies can quantify motion and force with high accuracy and repeatability that are not possible with standard clinical approaches.

1.6 Motion Capture and Modeling

Due to the complexity of the hand, motion capture and modeling are used in a laboratory setting to gain insight into the complex motions and forces at play. A few small studies have used modeling to evaluate interphalangeal (IP) joint and CMC joint motion in everyday tasks[1,51,58,70–73]. Although several studies have used motion capture and modeling to divide complex hand motions into component movements, only a few have applied modeling to pathological changes in the hand[58,72–76].

A few studies suggest that CMC joint kinematics, alterations in ROM, and joint deformities can be evaluated using motion capture[1,58,70,72,73]. Additional research is needed to further elucidate the pathophysiology of OA development and motion deficits. Such information would be useful to develop CMC joint specific OA diagnostic criteria, track OA progression, and quantify treatment success.

1.7 Biomechanical Risk Factors

Altered biomechanics (e.g. altered motions and forces) play a critical role in both OA development and progression. Most cases of OA develop after years of joint use, often in an environment of suboptimal biomechanics[11,54,77–79]. Biomechanical contributors to OA include joint laxity and instability, joint malalignment, elevated joint stress, and muscle strength and imbalance[6,11,56,80–82].

1.7.1 Joint laxity and instability

Joint laxity predisposes the joint to instability, leading to joint damage and increasing the risk for OA development[83]. Diseases that predispose individuals to increased joint laxity, or loose ligaments, frequently result in subsequent OA diagnosis[6,8]. For example, early onset OA is a well-known consequence of Ehlers-Danlos Syndrome, a genetic disorder characterized by altered collagen and connective tissue. Hypermobility and increased joint laxity are, by definition, associated with reduced joint stability, and increase the risk of joint injury[6,41,52,83]. Laxity can also lead to joint movement outside of normal ROM, resulting in inadequate transfer of loading forces and increased forces directed through the joint[77,84]. Joint laxity increases the contact area between articular surfaces, forcing new areas to experience abnormally high loads and subsequent cartilaginous wearing[53,77,85]. Additionally, research in the knee suggests that laxity may not only be a risk factor but also a consequence of OA[86].

Joint laxity creates an environment that adds stress to the other soft tissue supports surrounding the joint. If the non-ligamentous supporting tissues are not able to compensate for the loose ligaments, the joint will become unstable. The remaining soft tissue supports are especially important in the CMC joint because even a healthy CMC joint has relatively loose ligaments to allow for its large range of joint motion[54,87]. In the thumb, specific postures are linked with CMC joint instability. For example, key pinch tasks correlate with reduced CMC joint stability and translation of the trapezium[54,88]. CMC joint instability, defined by altered joint surface alignment, surface contact, and abnormal muscle actions, and has also been shown to lead to CMC OA[42,89].

1.7.2 Joint malalignment

Improper joint alignment is another biomechanical risk factor. Malalignment results in uneven joint wear, articular cartilage damage, and increased risk of OA[56,90–92]. For example, in the knee, malalignment is a well-described risk factor for OA development and progression[8,81,90,93]. Although the mechano-pathology is less researched in the thumb, dorsoradial subluxation of the first metacarpal and associated joint malalignment in the CMC joint, becomes more common as healthy individuals age[94]. More importantly, dorsoradial subluxation increases one's risk of CMC joint OA[80,94].

1.7.3 Joint stress

Increased joint load and high frequency of use stress the joint, predisposing one to OA development[1,8,10,11,23,41,52,95,96]. Excess joint stress can alter joint mechanics and cause abnormal joint loading[1]. Elevated joint stress leads to irreparable mechanical tissue damage and alternations to chondrocyte metabolism and gene expression which lead to downstream biochemical and local environmental changes[11,93,96,97].

1.7.4 Muscle strength and imbalance

Increased muscle strength is also a risk factor for hand OA development. When the hand grips an object, the forces felt by the joints increase as you move proximally. That is, the thumb IP joint experiences the least force, with increasing force in the metacarpophalangeal (MCP) joint, and finally the CMC joint, which is under the greatest magnitude of force[13]. Men with greater grip strength are at increased risk to develop OA in the first CMC joint and the MCP and PIP joints[98,99]. In women, this is associated with increased risk to the MCP joints[98,99]. Similarly, joint overuse increases the risk of OA development[100]. For example, regular chopstick use is associated with increased prevalence of OA in the thumb MCP joint and IP joint as well as the PIP and DIP of the 2nd and 3rd fingers[100].

Muscle balance and activation patterns are related to OA. Co-activity, or the activation of both agonist and antagonist muscles, is thought to be important for joint stability[97,101]. In the leg, increased ratio of quadriceps to hamstring strength and altered quadriceps muscle activation have been observed in patients with knee OA[97,102,103]. Although muscle atrophy was previously thought to be a consequence of disuse in OA patients, in the knee it has become evident that a muscle strength imbalance occurs much earlier[104,105]. Similar research to investigate the role of muscle in hand OA is needed.

Although increased grip strength is a risk factor for OA development, grip strength reduction is a well-known consequence of OA. Poor grip strength and muscle imbalance can be observed in hand OA patients[106]. Looking specifically at the thumb CMC joint, OA is also associated with reduced key pinch strength, tip strength, and tripod strength[88,106]. However, research investigating the effect of CMC OA on the relative strength of peri-CMC joint muscle groups is lacking.

1.8 Pathophysiology

Regardless of the risk factors involved, OA disease pathophysiology is similar. Years of repetitive use causes wear and tear on the articular cartilage. Due to its avascularity, cartilage cell turnover is very slow and its ability to regenerate is extremely limited. As one ages, the body’s minimal ability to repair and renew articular cartilage if further limited and the cartilage may become compromised[6,107,108]. As OA progresses, the articular cartilage wears away, joint space distance changes, and nearby structures like subchondral bone are exposed to new stresses[107]. Attrition of the cartilage and joint can distort the already compromised biomechanics, altering thumb CMC joint surface alignment and reducing joint movement and force generation[44,56,84,109,110]. These changes lead to patient reports of inflammation, tenderness to touch, reduced ROM, and joint pain that worsens with movement[9,11,61].

Inflammation occurs in early stages of hand OA[8]. When measured over a three month period, ultrasound revealed that inflammation features are consistently present in almost all hand OA patients over this time period[111]. However, lower rates of inflammation (10%) have been reported at a single time point[112,113].

In the hand, clinical diagnosis and staging are based upon the presence of hand pain or stiffening, tissue joint enlargement, and joint deformity. Early OA presents with joint effusion widening of the joint space and minimal subluxation. As OA progresses, the CMC joint space begins to narrow, articular cartilage becomes worn, the joint capsule becomes lax, joint debris begins to accumulate, and osteophytes start to appear on the dorsal portions of the trapezium. Later in the disease, CMC joint degeneration becomes evident on radiographic imaging and subluxation worsens. Osteophytes enlarge and the bone underlying the articular cartilage begins to show wear. The final stage of CMC OA presents with more significant joint space narrowing, degeneration of both the CMC and scaphotrapezium surfaces, and subchondral bone degeneration[114–116]. Future work to investigate earlier signs of OA development such as functional changes (changes in motion abilities and force production) or local inflammation could be useful to identify OA related changes, and thus provide treatment more quickly.

Long term studies suggest that joint space narrowing and osteophyte development continue to deteriorate joints in approximately 20% of patients for a minimum of two to 10 years[8,117]. Osteophyte progression seems to be more common in women, and is more likely to occur within 10 years of menopause[117]. This timeline further supports the potential role of hormones in OA and specifically osteophyte development; the dramatic reduction in estrogen that occurs at the onset of menopause may lead to osteophyte progression[117].

Radiographic changes are not synonymous with clinical deficits or pain. Although many studies have investigated the relationship between radiographic findings, pain, and functionality, few have found an association between imaging and the latter two[117,118]. However, numerous studies have shown a strong relationship between pain and functional deficits[117,118].

1.9 Treatment Options and Outcomes

OA diagnosis and treatment are generally initiated when the patient expresses joint pain concerns. First line treatment is most commonly acetaminophen or a non-steroidal anti-inflammatory prescription. Although the focus of OA treatment is pain management, early diagnosis and intervention can reduce long-term treatment costs and mitigate the impact of OA on hand function[25,41,119]. In lieu of the benefits of early treatment, conservative treatment frequently includes exercise therapy, lifestyle modification with a joint protection plan, and splinting of the affected joint(s).

Exercise in the form of physical and occupational therapist recommendations is the most cost-effective treatment for OA and is a cornerstone of treatment[62,63,120]. However, exercise prescription and the specific exercises prescribed are inconsistent[5,22,32,61,121–125]. The discrepancy between prescription and patient need is likely due to the lack of unbiased, high quality research studies evaluating the effects of specific exercise regimens[24,59,126].

When discussed in broad terms, most exercises fall into two categories: ROM (stretching, muscle release, etc.) and strengthening (resistance-based). In early stages of disease, most therapists prescribe both stretching and strengthening exercises. In later stages of disease, therapy prescription is based on one of two philosophies. The first is that joints with advanced OA should be treated with stretching exercises, but not strengthening exercises, as strengthening programs may worsen joint deterioration[32]. The second is that patients with advanced OA should be treated with stretching exercises which will increase ROM, and *then* can be treated with strengthening exercises[5]. Although care for advanced OA may be dictated by the prescribers belief in the impact of strengthening exercises on joint deterioration, no study has looked at the impact of exercise on joint angles in the thumb, and few have quantified the impact of exercise on motion and strength (force application) abilities[5,127–129]. Additional research is necessary to validate the use of hand exercises to improve quantitative hand function in CMC OA.

Studies have evaluated the effect of exercise specifically on patients who have hand OA with mixed results[5,22,123–125,129–133]. Those that have were rarely hypothesis driven; rather, they were developed by clinicians and therapists to substantiate their prescribed exercise regimens. This is likely the reason why most studies report outcomes based solely on validated, but subjective pain and function questionnaire scores. In the few studies that quantify hand ROM and hand grip strength changes following exercise, stretching regimens, strengthening regimens, and combined exercise regimens (with both stretching and strengthening components) have all reported similar gains[5,22,122–124,134]. To our knowledge, only one study was been conducted in persons with CMC OA to look at grip strength outcomes and none have looked at ROM; exercises studies have focused on subjective responses[122,124,134]. Further study is needed to evaluate the effects of hand exercise on objective, quantifiable function changes.

Second line treatment options for OA include joint injections and further pain management. However, many with thumb CMC OA eventually have pain severe enough that they seek the last line of treatment, surgical intervention. CMC joint surgeries are most commonly modifications of trapeziectomy. Since trapeziectomy began, ligament reconstruction and tendon interposition (LRTI) has been added to traditional trapeziectomy surgery in an effort to improve patient outcomes, namely reducing pain, improving and maintaining joint function, and preventing impingement[41]. Several studies have found that ligament and tendon alteration results in reduced pain, and improved grip strength[135,136]. However, these modifications may also increase side effects and risk of adverse outcomes[135]. Still, LRTI is considered the gold standard surgical option and the most commonly performed surgery in CMC OA patients[135,137,138].

In order to better improve patient care and hand function for the greatest number of patients, a thorough understanding of the benefits of early OA treatment must be determined. To help meet this overall goal, the work herein will provide evidence of the effectiveness of one key component of early OA treatment—exercise therapy. There is a strong need to develop *quantitative* measures to evaluate the effect of hand exercises on CMC joint function, namely the thumb and CMC joint specific kinematics and kinetics. This may aid the future development of gold standard CMC OA exercise recommendations.

The specific goal of this work is to quantify the effects of exercise on both thumb motion and force application. This document will provide therapists, physicians, and patients alike with data that quantifies the benefits of exercise therapy on thumb motions and force abilities in young healthy participants, older healthy participants, and participants with CMC OA.

CHAPTER 2: DETERMINING THE EFFECTS OF SHORT-TERM HAND EXERCISES ON THUMB FORCE GENERATION AND GRIP STRENGTH IN OSTEOARTHRITIC AND HEALTHY PERSONS

2.1 Abstract

Osteoarthritis of the carpometacarpal joint can dramatically impair thumb function resulting in the inability to complete basic tasks. Development of a measurement method to detect changes in thumb forces is essential to improving our understanding of the progression of carpometacarpal osteoarthritis and the effects of treatment. The goals of this study were to 1) develop a method to measure thumb forces in multiple directions, 2) demonstrate this method on three populations, young healthy (n = 23), older healthy (n = 11), and older participants with carpometacarpal joint osteoarthritis (n = 24), and 3) identify the effects of short-term (six weeks) exercises on thumb force production and grip strength in these three groups. Hand exercises improved thumb forces in young healthy female participants during radial (p = 0.017) and palmar abduction (p = 0.031) and female participants with osteoarthritis during palmar abduction (p = 0.010). Exercise improved grip strength in young healthy males (p = 0.028), young healthy females (p = 0.041), and females with osteoarthritis (p = 0.027). *Clinical significance:* Changes in grip strength do not necessarily correlate with changes in thumb strength; gathering thumb force data provides additional information for clinical assessment and treatment.

2.2 Introduction

Osteoarthritis (OA) at the base of the thumb, the carpometacarpal (CMC) joint, affects nearly 50% of Americans over 65 years old[8]. CMC OA causes a reduction in grip strength, poor range of motion, and joint pain, resulting in significant impairment of hand function[8,108,139–144]. The CMC joint has a unique saddle shape that allows the thumb to move in many directions, facilitating the completion of daily activities[145,146]. Everyday activities such as opening pill bottles, tying shoes, and grasping a glass of water become daunting tasks with OA[1,141,147].

Furthermore, the inability to conduct these basic tasks has the potential to result in a loss of independent living[4,19–21].

CMC OA alters grip strength and hand force production. Not only do individuals with CMC OA have reduced grip strength, they also have difficulties during hand opening and pinch grip[88,106,108,144,148]. To measure these forces, grip dynamometers are commonly used to obtain a single composite force generated from all the fingers together. A challenge with this approach is that the force data are non-specific to the digit and therefore, do not provide details with respect to the role of the thumb.

Current measures of grip strength utilized by clinics are not sufficient to determine thumb force abilities. Although a few devices can measure forces generated by the thumb in specific directions, none have been used to study individuals with CMC OA[145,149–157]. Some research reports have used the Rotterdam Intrinsic Hand Myometer to determine thumb forces in diseased populations, but not in OA[154].

Since the thumb exhibits complex movement, it is necessary to evaluate the thumb in postures that represent these movements. Thus, development of a measurement method to detect thumb forces in multiple directions is essential to improve our understanding of the effects of CMC OA. To better assess the effectiveness of targeted therapeutic interventions, a method to track thumb specific force production must first be developed and implemented. Multi-directional, thumb specific force data are critical for fine-tuning rehabilitation, to improve patient care, and to provide evidence of treatment effectiveness.

Exercise therapy is part of conservative OA treatment[63,158–160]. The goal of hand exercise is to increase hand function, namely by reducing pain, improving range of motion, and increasing grip strength. However, functional loss begins years prior to OA diagnosis. Several studies show that short-term hand therapy significantly increases overall grip strength both in individuals with hand OA and elderly individuals without OA diagnosis[5,22,124,125,161,162]. Little research is available to determine the specific effects of hand exercises on *thumb force* production.

Based on the gaps in research, the goals of this study were to 1) develop a method to measure isolated thumb forces in multiple directions, 2) demonstrate this method on three populations, young healthy, older healthy, and older participants with OA of the CMC joint, and 3) identify the effects of short-term hand exercises on thumb force production and grip strength in these three groups.

2.3 Methods

2.3.1 Participant testing

All testing and participant data were conducted in accordance with the University's Institutional Review Board. All participants were consented prior to data collection. Participants were right-handed and all data were collected on the right hand.

Participants in the young healthy (YH) group were required to be between the ages of 18-30 years old and participants in the older healthy (OH) and osteoarthritic (OA) groups were required to be between 55-80 years old. Inclusion criteria for the healthy groups: right-handed, no history of hand surgery, no hand therapy within the last three months, no medication changes within the last three months and no severe hand injuries, disease or illness, including hand OA. Inclusion criteria for the OA group: right-handed, doctor diagnosed hand OA, no history of recent hand surgery or therapy, no medication changes within the last three months, and no hand injuries, disease, or illness, other than OA. Presence of hand stiffness, aching and/or pain in our joint of interest, the right first CMC joint, was required for inclusion in the OA.

All participants were tested at three time points over six weeks. For each time point, data were collected at the same time of day. Time point one (week 0) data were collected at their initial visit prior to intervention. Time point two (week 2) data were collected following two weeks daily hand stretching exercises. Time point three (week 6) data were collected following four weeks of daily hand stretching and strengthening exercises. The order of dynamometry and thumb force application tests were randomized across participants. Basic demographic information, thumb force, and grip strength data were collected from participants at three time points.

2.3.2 Exercise protocol

The exercise protocol included both stretching and strengthening exercises (Figure 2-1) and was developed in conjunction with a hand therapist. The first two weeks was composed of exercises designed to stretch the first web space and improve joint alignment during grip tasks. Exercises included passive range of motion (ROM), active ROM, and manual medicine techniques. After two weeks, participants were retested and given a second set of exercises to be completed in addition to the stretching exercises.

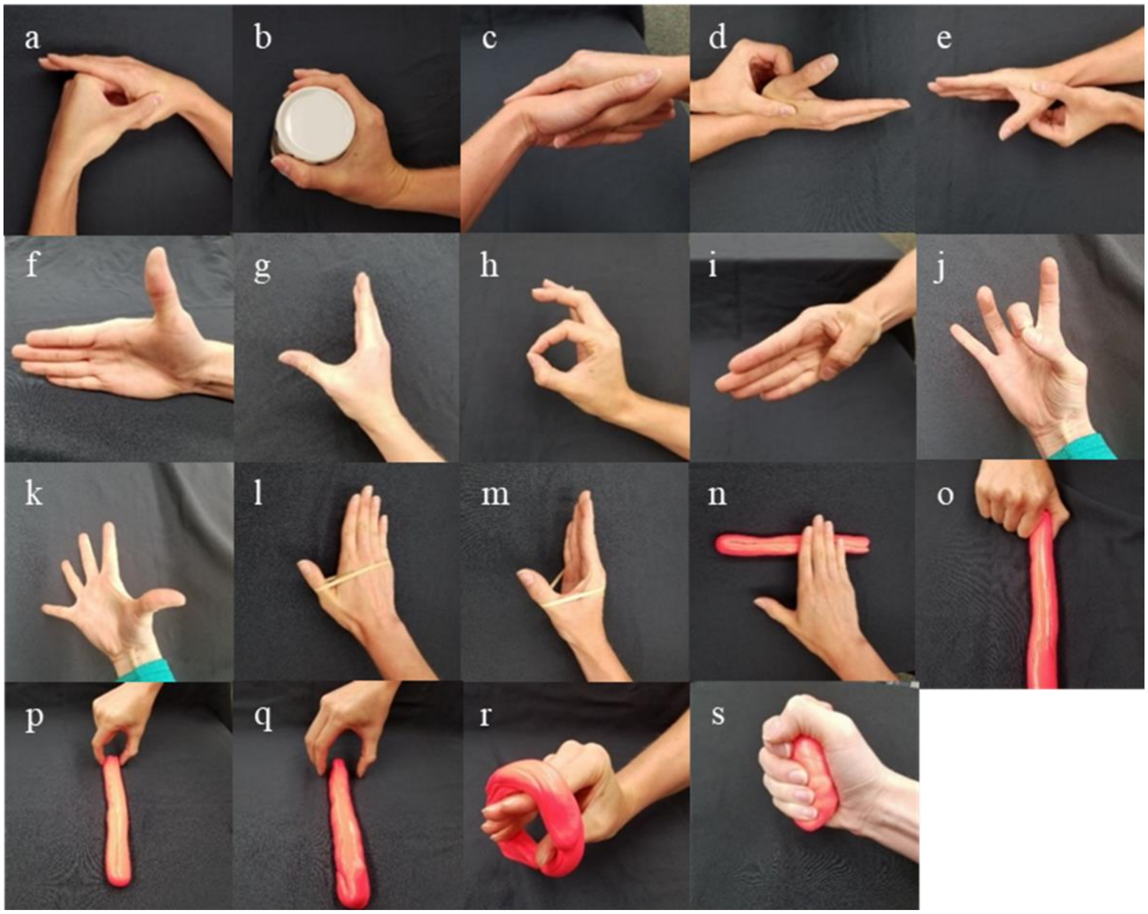

Figure 2-1: Hand exercise regimen.
Stretching exercises included osteopathic and muscle release techniques: a) first web space release, b) first web space cone stretch, and c) bilateral web space stretch; passive range of motion exercises: d) passive radial abduction, e) passive palmar abduction; and active range of motion exercises: f) active radial abduction, g) active palmar abduction, h) okay sign, i) opposition to the base of the fifth finger, k) opposition to each fingertip, and k) finger spread. Strengthening exercises included therapy band exercises: l) resisted radial abduction and m) resisted palmar abduction; and putty exercises: n) putty roll, o) key pinch, p) okay sign pinch, q) three finger pinch grip, r) resisted finger spread, and s) putty squeeze.

The second set of exercises were conducted for four weeks and designed to improve hand strength, focusing on the peri-first metacarpal muscles. Exercises included resistance-based active ROM and resistance-based grip tasks using therapeutic bands and putty. All participants were asked to complete the exercises a minimum of once daily. Additionally, participants were contacted periodically throughout the study to check for adverse effects, to remind participants to complete the exercises daily, to answer any questions they had, and to confirm future appointments.

2.3.3 Thumb force measurement device

Thumb force datasets were collected using an AMTI multi-axis load cell (Watertown, MA) and a custom-built apparatus (Figure 2-2). The vertical height, the distance from load cell, the angle of hand inclination between the base plate and ulnar side of the hand, and the diameter of ring of the apparatus were adjustable. Tubing was positioned along the inner diameter on the ring as needed to ensure a snug fit while thumb placement was maintained in the center of the ring. Both the tubing and various sized wedges were used to ensure the thumb rested with the metacarpophalangeal joint parallel to the ring. The right hand was placed with the palm against the medially located hand support and the ulnar side of the hand flat against the base plate.

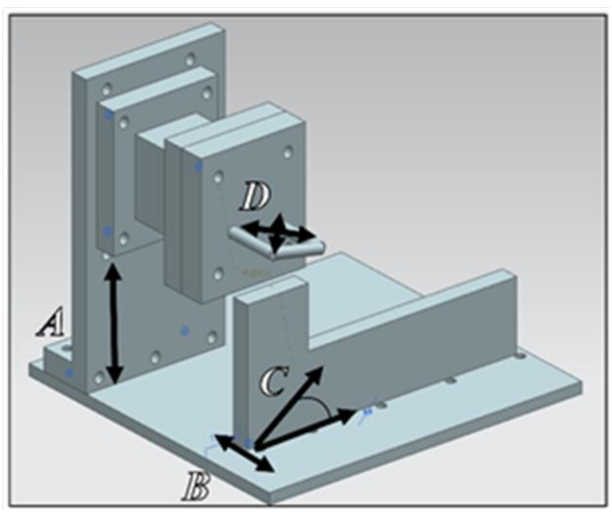

Figure 2-2: Computer model of device adjustability.
Adjustments can be made to a) the load cell height, b) the distance of the hand support from load cell, c) the angle between the base plate and ulnar side of hand, and d) the diameter of ring where thumb applies force.

Thumb forces were collected in four directions (Figure 2-3): 1) radial abduction (RAB), 2) radial adduction (RAD), 3) palmar abduction (PAB), and 4) palmar adduction (PAD). Participants were instructed to use their thumb to press against the ring in the specified direction with as much thumb force as they could without using other parts of their body. Thumb forces were collected three times in each direction. To match the clinical protocol of dynamometry (discussed below), the largest force applied from the three replicates (for each thumb direction) was used for analysis.

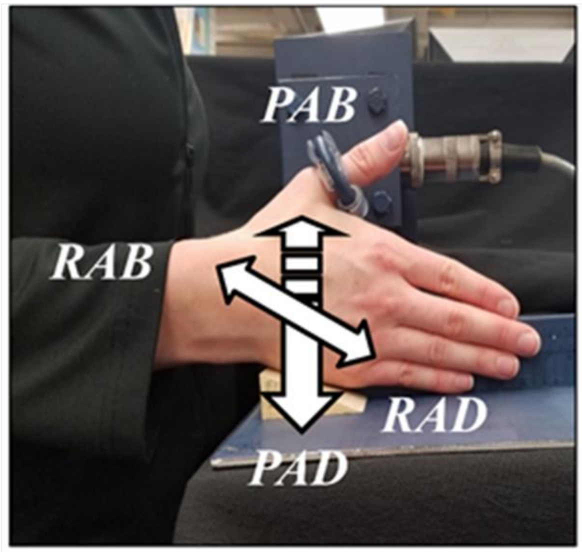

Figure 2-3: Load cell apparatus.
Forces were applied in the following directions: radial abduction (RAB), radial adduction (RAD), palmar abduction (PAB), and palmar adduction (PAD). Tubing was used to adjust the internal diameter of the ring and various sized wedge.

2.3.4 Hand grip dynamometry

Grip strength was collected using a Sammons Jamar Hydraulic Hand Dynamometer (Model 31204071, Bolingbrook, IL). All dynamometry protocols were performed in the same fashion as they would be performed in a clinical setting[144,163,164]. All participants had their maximum grip strength measured using grip #2 (handle distance 1 7/8 in or 4.76 cm) and #3 (handle distance 2 3/8 in or 6.03 cm) in triplicate. The largest force applied from the three replicates (for each grip) was used for analysis.

2.3.5 Statistical Analysis

Two main analyses were conducted. First, a repeated measures ANOVA was used to compare across time points to determine the effects of exercise for all six groups (two sexes in each of the three participant groups) and a Bonferroni t-test was used to determine significance between time points. Because prior research has shown that there are magnitude differences between sexes, the sexes were evaluated separately[163,165]. Next, a one-way ANOVA was used to compare the force differences between sex specific YH, OH, and OA group data with SigmaStat (Systat, San Jose, CA) at each time point and Holm-Sidak method was used to determine statistical differences; a p-value < 0.05 was considered statistically significant. Data was tested for normality using Shapiro-Wilk and for equal variance using Brown-Forsythe. In the case that normality or equal variance failed, Kruskal-Wallis ANOVA on Ranks was used; Dunn's post-hoc comparison was used to determine significant differences between specific groups.

2.4 Results

2.4.1 Participants

A total of 58 individuals participated in this study with 50 completing all six weeks of exercise:

1) 23 young healthy (21 completed all six weeks), average age 22.5 years ± 3.1 years, 12 males,

2) 11 older healthy (9 completed all six weeks), average age 66.3 ± 8.4 years, five males, and

3) 24 participants with CMC OA (20 completed all six weeks), average age 69.4 ± 5.8 years, six males.

2.4.2 Thumb force generation trends prior to intervention

The largest thumb forces produced by all groups were applied during radial adduction (week 0 females: 38.1 N in YH, 35.3 N in OH, and 25.2 N in OA; males: 54.6 N in YH, 49.8 N in OH, and 54.8 N in OA). Most participants had greater radial and palmar adduction forces than abduction. For all directions, females produced less forces than males.

2.4.2.1 Female groups

Statistically, OA females produced significantly less thumb force during radial adduction and palmar abduction than YH females (p = 0.020 and p = 0.020 respectively; Figure 2-4). Prior to exercise, the largest forces in all female participant groups were produced during radial adduction, followed by palmar adduction, palmar abduction, and then radial abduction.

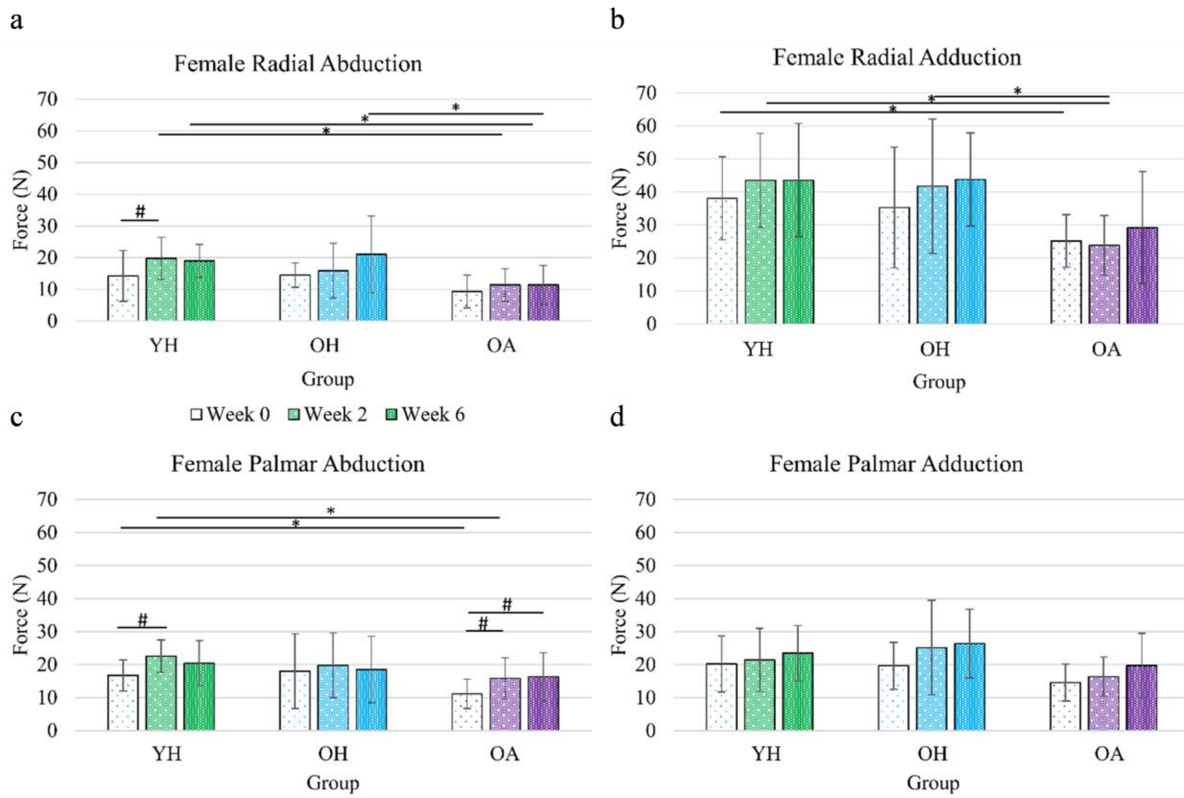

Figure 2-4: Female thumb force application.
Force application occurred during a) radial abduction, b) radial adduction, c) palmar abduction, and d) palmar adduction. * denotes a significant difference between the indicated groups at a given time point. # denotes a significant difference for a given participant group between the indicated time points. Data is shown are group averages ± standard deviation.

2.4.2.2 Male groups

Prior to exercise, the forces produced by males varied by group and differences were not as large as those generated by females. YH and OA male participants produced the greatest forces during radial adduction, followed by radial abduction, palmar abduction, and then palmar adduction. OH males had their greatest forces during adduction (radial adduction then palmar adduction) followed by abduction (palmar abduction then radial abduction; Figure 2-5).

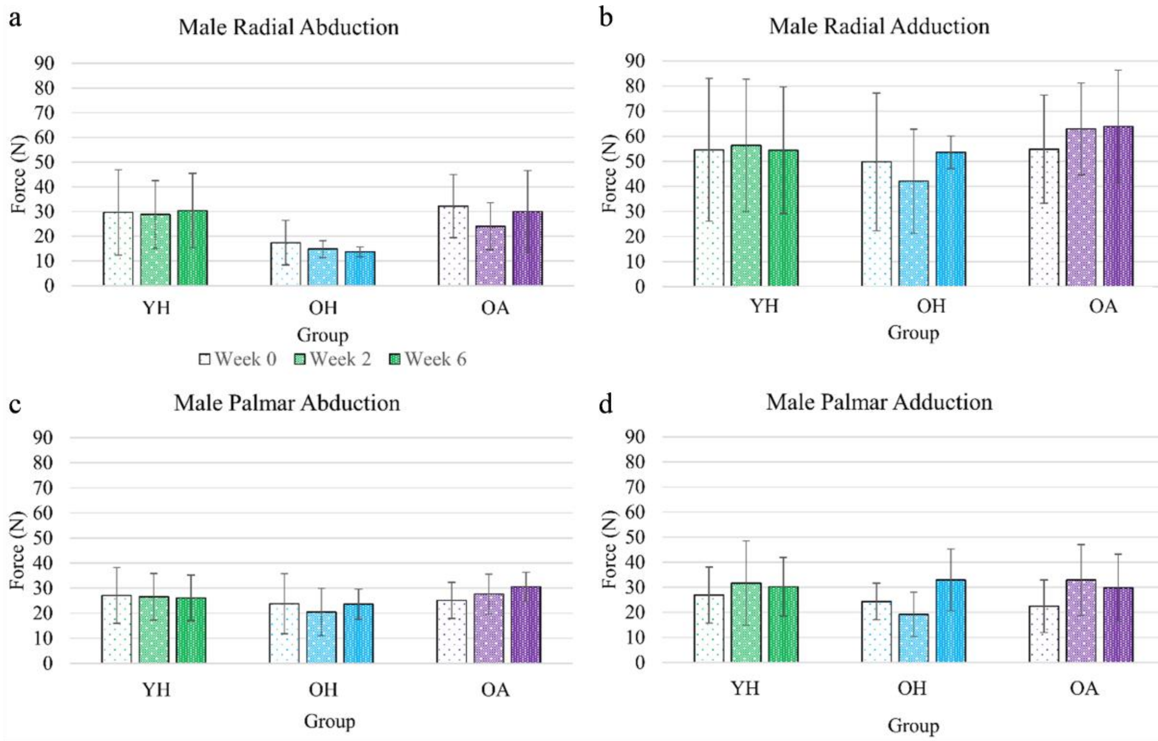

Figure 2-5: Male thumb force application.
Force application occurred during a) radial abduction, b) radial adduction, c) palmar abduction, and d) palmar adduction. No statistically significant differences were found between groups at given time point or within groups following exercise. Data is shown are group averages ± standard deviation.

In summary, the results show that participants of most generated more force when the thumb was moving towards the palm (adduction) than away (abduction) for both palmar and radial cases. The YH group produced larger forces than the older groups but statistical differences were only seen in the female groups.

2.4.3 Effects of exercise on thumb force generation

2.4.3.1 Female groups

YH females produced significantly greater radial adduction and palmar abduction forces ($p = 0.0001$ and $p = 0.033$, respectively) following two weeks of hand exercises than OA participants; this was also true for radial abduction forces following six weeks of exercises ($p = 0.036$). OH females also produced significantly greater radial adduction forces than OA females after two weeks and greater radial abduction force after six weeks ($p = 0.021$ and $p = 0.027$, respectively). When looking for the average improvement across all four directions, female participant groups had similar increases in thumb force generation (~4.5 N increase on average of all force directions).

Exercise increased female force generation in all directions with the biggest effect after two weeks of stretching exercises. Exercise significantly improved radial abduction thumb force in YH female participants following two weeks of stretching exercises ($p = 0.025$). Increased radial abduction ability was maintained following six weeks of exercise. Additionally, after six weeks of exercise, palmar abduction force generation was significantly greater than pre-exercise (week 0) values in YH females ($p < 0.001$). Although both OH and OA females improved their force generation following exercise, only palmar abduction in OA females was significant (week 0-2 $p = 0.039$ and week 0-6 $p < 0.01$, respectively).

2.4.3.2 Male groups

On average, YH male thumb force generation increased 0.05 N, OH increased by of 2.2 N, and OA by 5.6 N across all force directions after exercise. Exercise did not have a significant effect on thumb force generation in male participant groups, however positive trends were shown primarily in the two older participant groups. When looking at changes in specific directions following exercise, YH male participants increased force generation in palmar adduction only (3.3 N at week 6). OH participants increased their radial and palmar adduction force generation (3.8 N and 8.6 N, respectively at week 6), but not their radial or palmar abduction force. OA participants improved force generation in every direction following exercise (increases of 0.3 N in radial abduction, 9.1 N in radial adduction, 5.4 N in palmar abduction, and 7.4 N in palmar adduction at week 6). However, no increase was statistically significant in our male sample (Figure 2-5).

In summary, exercise increased force generation in all thumb directions for all female participants and had a limited effect on male thumb forces. Additionally, when comparing the effects of the two weeks of stretching exercises to the four weeks of combination exercises, the stretching exercises resulted in greater thumb force increases in the female participants.

2.4.4 Grip strength trends prior to intervention

All participant groups had similar grip strength using both grips #2 and #3. Trends for improvement were often the same for both grips, however statistical significance varied by sex and the grip used. As expected, male participants exhibited greater grip strength than females.

2.4.4.1 Female groups

Female grip strength was stratified by group. YH had significantly greater grip #2 and #3 strength than OH and OA females prior to exercises (vs. OH grip #2 $p = 0.009$ and grip #3 and $p = 0.035$; vs. OA grips #2 and 3 $p < 0.001$, respectively).

2.4.4.2 Male groups

YH males had greater grip strength than OH or OA participants, although not statistically significant. There were no significant differences in grip strength between any male groups for either grips.

2.4.5 Effects of exercise on grip strength generation

2.4.5.1 Female groups

YH participants had significantly greater grip strength than OH participants following two weeks of exercises ($p = 0.022$ for both grips #2 and #3), but not after six weeks (grip #2 $p = 0.089$ and grip #3 $p = 0.080$). YH participants also had significantly greater grip strength than

OA females for both grips following exercise ($p < 0.001$ for both grips at both two and six weeks).

Exercise improved grip strength in all female participant groups. YH females significantly improved grip strength following exercise (grip #2 $p = 0.041$ and grip #3 $p = 0.033$, respectively). OH and OA participants also increased their grip strength following exercise, however only grip #2 was significant (OA grip #2 $p = 0.0440$, grip #3 $p = 0.427$ and OA grip #2 $p = 0.027$, grip #3 $p = 0.058$).

2.4.5.2 Male groups

Two and six weeks of hand exercises increased hand grip strength significantly in YH male participants using grip #2 ($p = 0.008$ and $p = 0.029$, respectively). Although both OH and OA males had improvements in both grip strength #2 and #3 following exercise, the changes were not significant.

In summary, exercise increased grip strength in all participant groups using both grips. Significant improvements were seen in both sexes following exercises when using grip #2.

2.5 Discussion

The goals of this study were to 1) develop a method to measure isolated thumb forces in multiple directions, 2) demonstrate this method on three populations, young healthy, older healthy, and older participants with OA of the CMC joint, and 3) identify the effects of short-term hand exercises on thumb force production and grip strength in these three groups.

To accomplish the first goal, a custom apparatus attached to a multi-axis load cell was designed and then manufactured. The device was successfully able to isolate thumb forces from other fingers and measure thumb force production in four directions: radial abduction, radial adduction, palmar abduction, and palmar adduction. The device was then tested in the three groups of participants before, during and after a six-week exercise regimen. These previously unavailable datasets are clinically valuable—they provide insight into the effects of OA on thumb function and force production. Specifically, these data have the potential to provide feedback and assessments for one of most critical joints in the hand, the CMC joint at the base of the thumb. When this joint is not functioning properly, people lose the ability to complete day-to-day tasks affecting their quality of life[4,19–21]. This work permits focused assessments of the thumb, allowing us evaluate changes in force production and to monitor treatment success, and to determine whether modifications in the treatment strategies are necessary. In those with functional impairments, even small increases in force production or range of motion due to exercise can lead to clinically significant improvements in the ability to complete basic tasks. In individuals with CMC OA, these improvements can be the difference between successfully completing daily tasks and loss of independent living.

2.5.1 The relationship between thumb forces and grip strength

Clinically, grip strength is used as an indicator of hand function in CMC OA, and thus it is assumed that a change in grip strength in persons with CMC OA is indicative of a change in thumb strength. However, thumb forces cannot be separated from the hand grip strength profile. Furthermore, our evaluation of isolated thumb data indicates grip strength does not reliably indicate thumb function. For example, hand exercises significantly improved hand grip strength in YH male participants, but this was not accompanied by an increase in thumb force generation. Therefore, our data suggests that the increased force production found in YH participants following exercise is originating from digits other than the thumb. This difference illustrates that thumb and grip trends may not be interchangeable, and suggests thumb forces are necessary in a clinical setting to follow injury and disease affecting force production in the thumb. OA males in our study had similar grip strength improvements as YH males following exercise, but OA males had larger thumb force gains. This further suggests that grip and thumb force data are not equivalent.

2.5.2 Thumb force generation trends prior to intervention

By measuring forces in multiple groups and sexes, we were able to identify common trends and differences between these groups. Our dataset not only adds to the no intervention male data captured by Li and Harkness, but also creates female and CMC OA datasets[153]. To the authors' knowledge, no other group has published healthy and CMC OA isolated thumb force datasets within a single study[149,152,153]. One study by Li and Harkness obtained continuous circumferential thumb force data from seven college-aged men using a multi-axis load cell. When the thumb was in specific positions like radial abduction, the force data were extracted from the continuous dataset. The force data reported was larger than those reported in our study, however Li and Harkness indicated that "it is possible the force magnitude in a specific direction obtained by continuous exertion is different from the force generated in the same direction during a focused unidirectional effort"[153].

2.5.3 Effects of exercise on thumb force generation

Results indicate that the exercise regimen was sufficiently difficult to elicit changes in females, but not males. In females, OA participants improved their force application such that there was no longer a significant difference between YH and OA forces during radial adduction and palmar abduction. This suggests that the effect of exercise, in particular stretching exercises, may be clinically beneficial in OA participants. If performed early, prior to OA diagnosis, our data indicate that exercise allows individuals to regain lost force abilities. Female participant groups had a larger increase in force production with statistically significant differences between time points. Healthy male participants experienced smaller improvements with no statistically significant results. Based on these sex-specific results, the exercise program may have been sufficiently difficult for female participants to elicit a change, but not strenuous enough for healthy male participants to see a similar benefit.

2.5.4 Grip strength trends prior to intervention

Similar to other studies, males had greater hand grip strength than females, and younger participants had higher grip strength force generation than older individuals[108,139,144,163,166]. Additionally, the magnitudes of OH grip strength data reported here are similar to those published by Jensen[163]. It is likely that the decreased grip strength seen in OA participants is due not only to muscle weakness, but also due to the altered biomechanics and greater forces felt at the already painful CMC joint[167].

2.5.5 Effects of exercise on grip strength generation

Our work suggests that just two weeks of stretching exercises significantly increased grip strength in the male and female YH participants, and female OA participants. This recapitulates findings by other clinicians and researchers, and further shows improvements can occur in both healthy and diseased group in a much shorter time period than previously reported[125,166,168].

2.5.6 Limitations

To our knowledge, this is the first study to evaluate the effect of exercise intervention on multi-directional thumb forces. Although many of the results in this study are promising, not all the trends are statistically significant. Future studies with a larger number of participants, in particular, the inclusion of a larger number of older healthy participants, would benefit the hand research community to further validate the findings herein and aid the comparison between OH and OA participants.

2.6 Conclusions

Understanding of the impact of exercise on thumb force application is critical to evaluate the effectiveness of CMC OA treatment on thumb function. In this study, we successfully identified changes in thumb force generation due to short-term hand exercises in YH, OH, and OA participants. These findings support the use of the stretching and strengthening exercises to target peri-first metacarpal muscles, and as little as two weeks of stretching exercises demonstrate statistically significant changes in thumb forces in females and grip strength in males and females.

Based on this research, we can begin to observe the relationships between forces generated by the thumb and generalized hand strength. Grip strength is not predictive of changes in thumb forces; based on the data, collection of separate thumb forces are necessary to evaluate thumb function and intervention success.

To our knowledge, this study is the first to 1) develop a quantifiable method to compare thumb forces in healthy and diseased thumbs, and 2) investigate the effect of exercise on thumb forces in both healthy and OA participants. Understanding the effects of exercise on thumb forces will allow researchers and clinicians to better develop targeted therapies and track outcomes specific to the thumb.

CHAPTER 3: COMPLEX THUMB MOTIONS AND THEIR POTENTIAL IN IDENTIFYING MOTION CHANGES RELATED TO OSTEOARTHRITIS EARLIER THAN STANDARD MEASURES

3.1 Abstract

Early diagnosis and treatment of osteoarthritis allows for early interventions that may mitigate osteoarthritis progression and decrease severity later in life. Early identification of motion changes is limited by the clinical reliance on single planar measurements using goniometry. Multi-planar measurements using motion capture can provide insights into joint function and pathophysiology that cannot be obtained from single-plane goniometry measurements. Thus, the goals of this research were 1) to determine differences in thumb motions across three groups of participants (young healthy (n=23), older healthy (n=11), and those with carpometacarpal osteoarthritis (n=24)) and 2) to determine if multi-planar motions provided additional movement information in comparison to standard planar measures. In this study, a motion capture system was used to collect standard clinical ranges of motion and motions during three multi-planar tasks. Thus, differences in motion patterns due to aging and osteoarthritis were identified. Motions tested included palmar adduction-abduction, radial adduction-abduction, metacarpophalangeal flexion-extension, interphalangeal flexion-extension, functional adduction-abduction, opposition, and circumduction.

Results indicated that motion capture was capable of detecting changes in carpometacarpal mobility that were not detected using standard approaches. Our results suggested that use of multi-planar measurements may be able to identify changes that are indicators of early stages of osteoarthritis. Early indicators are clinically useful as they will enhance patient treatment by permitting the application of treatment approaches sooner, potentially leading to reduced overall functional deficits.

3.2 Introduction

Osteoarthritis (OA) is a prevalent disease with one in every two Americans over the age of 65 affected by carpometacarpal (CMC) OA[8]. OA causes cartilage attrition and can damage the underlying bone[8]. In the thumb CMC joint, OA presents with reduced range of motion, joint pain, and poor grip strength[8,141,142]. In order to oppose the thumb and to grasp objects, the large range of motion at the CMC joint is critical; loss of CMC motion significantly impacts a person's life. This motion impairment can lead to the loss of personal independence and result in the need for nursing care[1,4,19–21,75,169,170].

Early diagnosis and treatment of OA can mitigate progression and disease severity later in life[171]. To improve outcomes in those with OA, we must first decrease the time between disease onset and diagnosis. Earlier identification of motion changes that are related to OA formation will allow for earlier treatment and preservation of hand function.

Identification of motion changes in CMC OA is limited by the clinical reliance on planar measurements. In a clinical setting, a goniometer (similar to a protractor) is used to measure ranges of motion in a single plane. However, the axes of CMC motion are non-perpendicular and do not align with the planes of the body, so it is difficult to assess complete function of the CMC joint by only taking goniometer measures[55,64]. Goniometers have poor inter-rater reliability, and this reliability is even worse when measuring the CMC joint[66,67,172,173]. Joint deforming diseases like OA, along with the complex motion patterns make it even more challenging to measure CMC motion using a goniometer[170]. Due to these factors, it is difficult to use a goniometer to identify early CMC OA motion loss or to determine the efficacy of a given treatment.

To improve measurement abilities, alternative clinical methods have been developed to obtain single movements of the thumb, specifically, thumb palmar abduction[174,175]. Although useful, improvement in measurements for palmar abduction do not improve on the other thumb motions. Neither goniometry nor alternative clinical methods are capable of measuring the complex multi-planar motions of the CMC joint.

Multi-planar measurements can provide insight into joint function and pathophysiology that cannot be obtained from planar goniometry measurements. Motion capture systems (i.e. cameras and reflective markers) are capable of measuring multi-planar motions. Marker based motion capture systems are able to measure small movements, and have been shown to be an excellent method to measure CMC motion with greater accuracy than goniometry[65,68,69,176]. The use of motion capture is also becoming more popular in clinical settings such as its use in the Shirley Ryan Ability lab, in surgical training programs, and post-surgery evaluation[177–179].

The full capacity of motion capture to study CMC OA has not been determined. Although a few studies have evaluated hand motion, these are primarily limited to a small number of participants, usually healthy persons[1,2,49,58,72,75,76,176,180–191]. No single study has collected standard clinical ranges of motion and multi-planar motion capture data in healthy and CMC OA participants to identify the differences between the participant groups. Three-dimensional (3D) motion data collection in both normative and diseased thumbs is necessary to better understand the complex multi-planar motion changes that occur during aging and in CMC OA pathophysiology. Thus, the goals of this research were 1) to determine differences in thumb motions across three groups of participants (i.e., young healthy, older healthy and those with CMC OA) and 2) to determine if multi-planar motions provided additional movement information in comparison to standard planar measures.

3.3 Methods

3.3.1 Testing

All testing and participant data were conducted in accordance with Michigan State University's Institutional Review Board and all individuals consented to participation. Participant data collection included the following: American College of Rheumatology criteria, visual analogue scale (VAS) pain score, functional index for hand osteoarthritis (FIHOA) questionnaire, and motion testing[107].

3.3.2 Participants

All participants were right-handed. Inclusion criteria for the healthy groups was that they had no history of hand surgery or recent hand therapy (<three months), they did not have a severe hand injury, disease, or illness, including hand OA, and no recent medication changes (<three months). Inclusion criteria for the OA group was that participants had been diagnosed by a doctor as having hand OA presenting with symptoms consistent with OA of the right thumb CMC joint (stiffness, joint pain, reduced strength, etc.), had no recent history of or upcoming plans for hand surgery or therapy, and no hand injury, disease or illness, other than OA[107]. Young healthy (YH) recruited participants were age 18-30, and both older healthy (OH) and CMC OA participants (OA) were age 55-80.

3.3.3 Motion capture

Motion data were collected using a seven camera Qualisys Motion Capture System (Gothenburg, Sweden) and reflective markers. Data were collected from each participant's right hand using 36 markers (eight single markers and seven pods) placed on the right hand and wrist at the following locations: thumb metacarpal, proximal phalanx, distal phalanx, proximal, middle, and distal phalanges of the index finger, and the palm. Individual markers were placed on the second-fifth metacarpophalangeal (MCP) joint, ulnar side of radial styloid, proximal radius, mid-wrist (ulnar side of Lister's tubercle), and ulnar styloid (Figure 3-1). All motions tested were completed in triplicate, with the exception of circumduction in which five revolutions was completed. Prior to data collection of each motion, the participants were verbally told and shown how to complete the motion of interest. The order of all motions, both standard clinical and multi-planar motions were randomized for each participant.

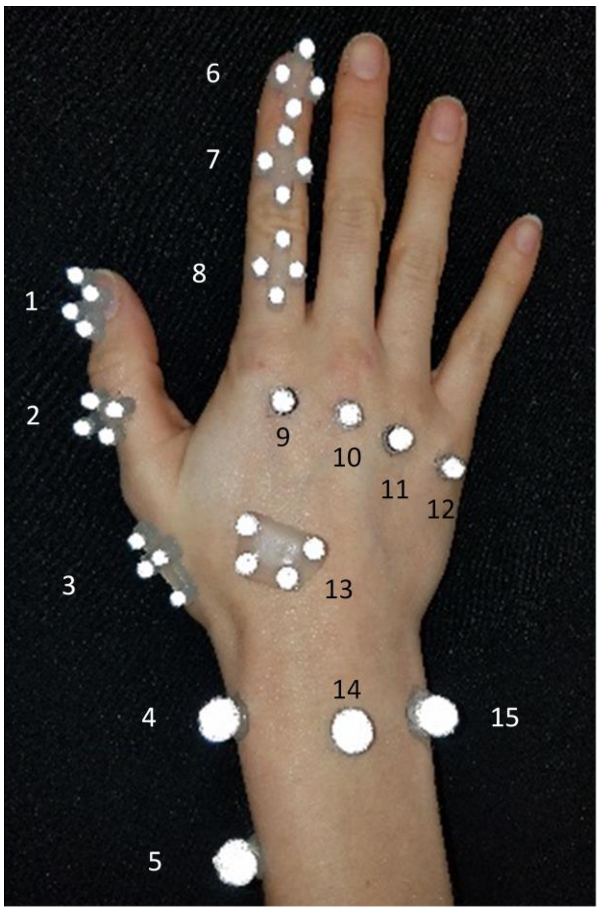

Figure 3-1: Motion capture marker placement.
Rigid four marker pods were placed on each thumb and index segment and single markers were placed on bony landmarks. Markers are as follows: 1-thumb distal phalange, 2-thumb proximal phalange, 3-first metacarpal, 4-ulnar side of radial styloid, 5-proximal radius, 6-index distal phalange, 7-index middle phalange, 8-index proximal phalange, 9-2nd metacarpophalangeal joint, 10-3rd metacarpophalangeal joint, 11-4th metacarpophalangeal joint, 12-5th metacarpophalangeal joint, 13-palm, 14-mid-wrist, and 15-ulnar styloid.

3.3.3.1 Standard ranges of motion and calculations

Standard ranges of motion were those movements that are typically evaluated in a clinical setting using a goniometer. These motions were performed with the motion capture system. Tests included palmar adduction-abduction, radial adduction-abduction, metacarpophalangeal flexion-extension, and interphalangeal flexion-extension.

Participants were verbally and visually shown each motion and asked to reach as far as they could when completing each motion. To measure each range of motion, the angles between the vectors labelled 1 and 2 were determined using all three components (x,y,z) of that marker position. Angles were computed at the beginning and end of each motion using the two vectors defined in Table 3-1 and Equation 3-1. The range of movement was then calculated by obtaining the difference between the start and ending angles (Figure 3-2). For the MCP and interphalangeal (IP) joints, the individual values of flexion and extension were identified. These were defined from the neutral position of the joint, which was when the two vectors were parallel and the angle between the vectors was zero. Regardless of direction, all angles are reported as positive to avoid confusion.

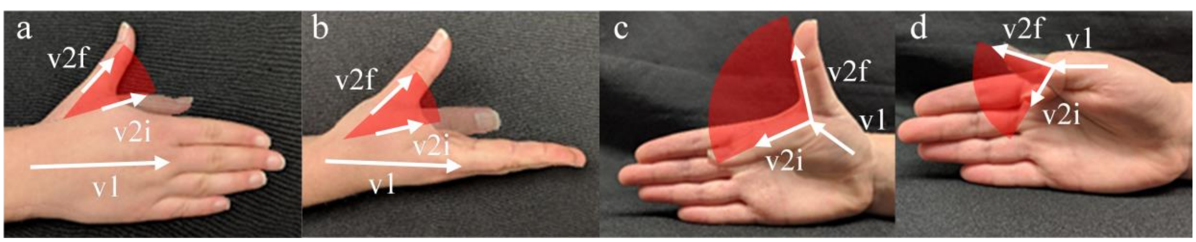

Figure 3-2: Standard range of motions tested in a clinical setting and the associated angles measured using motion capture.
To determine the range of motion for each relevant joint, the angle was measured between vector 1 (v1) and vector 2 (v2i; at the start of the action) and (v2f; at the end of the action) a) radial adduction-abduction, b) palmar adduction-abduction, c) metacarpophalangeal flexion-extension, and d) interphalangeal flexion-extension.

Table 3-1: Vectors used to calculate range of motion with vectors created from motion capture markers.

Motion/Angle Name	Vector 1 Markers	Vector 2 Markers
Palmar (and Functional) Adduction-Abduction	2nd MCP-radial styloid	1st MCP distal-1st MCP proximal
Radial Adduction-Abduction	3rd MCP-midwrist	1st MCP distal-1st MCP proximal
MCP flexion and extension	1st metacarpal distal- 1st metacarpal proximal	1st MCP distal-1st MCP proximal
IP flexion and extension	1st MCP distal-1st MCP proximal	IP distal-IP proximal
CMC angle (opposition)	radial styloid-proximal radius	1st metacarpal distal-1st metacarpal proximal
MCP angle (opposition)	1st metacarpal distal-1st metacarpal proximal	1st MCP distal-1st MCP proximal
IP angle (opposition)	1st MCP distal-1st MCP proximal	IP distal-IP proximal

$$\Theta = \cos^{-1}\left(\frac{\boldsymbol{V_1} \cdot \boldsymbol{V_2}}{|\boldsymbol{V}_1||\boldsymbol{V_2}|}\right)$$

Equation 3-1

3.3.3.2 Multi-planar motions and calculations

Multi-planar motions included: functional adduction-abduction, opposition of the thumb to the base of the fifth metacarpal, and circumduction. These motions were termed multi-planar because, unlike standard motions tested in clinic, they were complex motions selected to include multiple planes of motion (Figure 3-3). Participants were verbally and visually shown each motion prior to completion.

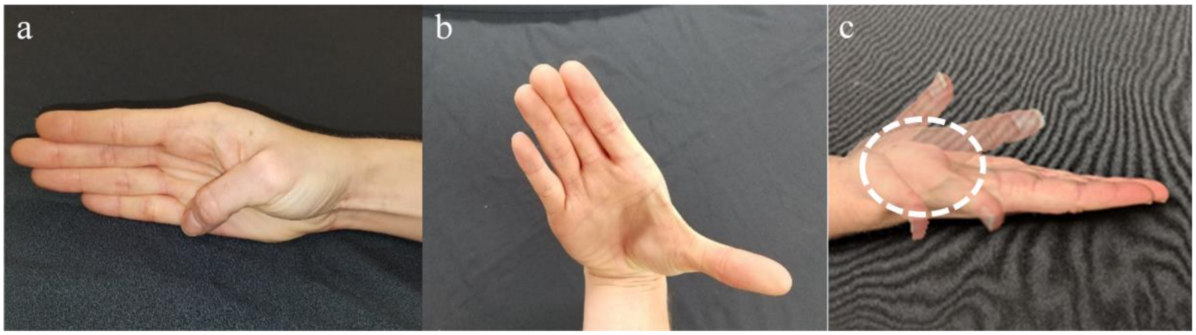

Figure 3-3: Multi-planar motion tasks tested.
Motions included a) functional adduction-abduction, b) opposition, and c) circumduction. The dotted circle on panel c shows the approximate path of motion of the first metacarpal.

Opposition

For opposition, participants were asked to reach the tip of his/her thumb to the base of his/her fifth finger (they were given a target location to reach for). Although opposition can be measured in a clinical setting using a goniometer it is not typically measured.

Opposition measures were obtained by computing the distance between the distal most marker on the tip of the thumb pod (distal phalange pod) and the marker on the dorsal side of the fifth MCP. Smaller distances were indicative of the tip of the thumb being closer to the fifth MCP joint (better opposition ability). The motion capture frame with the minimum distance between the distal phalange pod and fifth MCP marker was the frame of interest and the point for which CMC, MCP, and IP angles were calculated during opposition.

Circumduction area

Circumduction was the movement of the thumb in a circular fashion while trying to achieve the largest shape possible. They completed five repetitions of counterclockwise thumb circumductions for each test.

Circumduction area was determined by using Principal Component Analysis (PCA). The positions of the most distal marker on the first metacarpal were recorded during circumduction. PCA was used to identify a plane in space for the computation of an area. This was done by minimizing the distances between the data points collected (based on the position of the distal most first metacarpal marker) and a plane in three dimensions. The total area encompassed by the projections of the points onto that plane was collected for each revolution (Matlab, Mathworks). Area results were normalized by thumb metacarpal length. An example of the circumduction data are shown in Figure 3-4. The circumduction codes are shown in Appendix B.

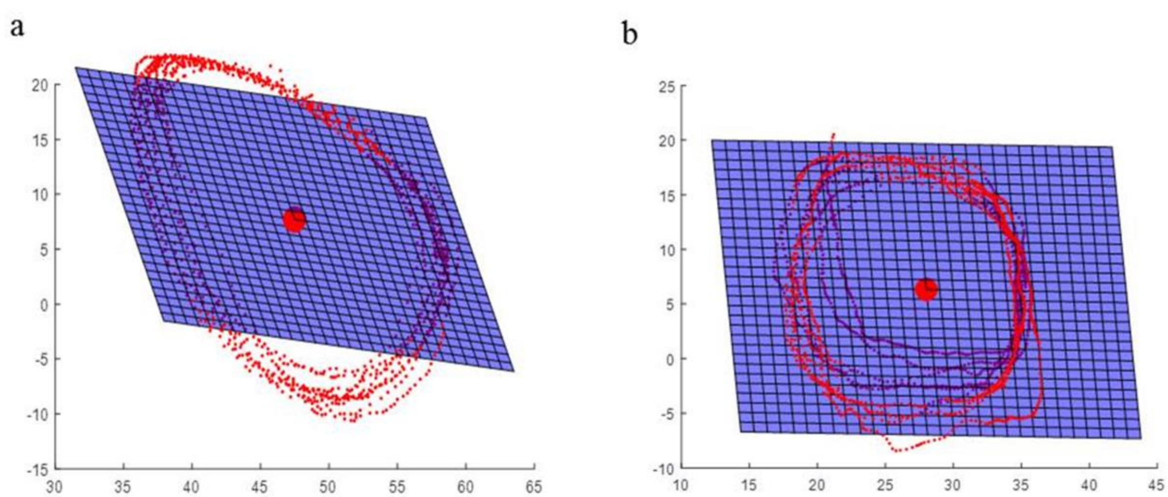

Figure 3-4: First metacarpal tracing during circumduction.
Representative images of first metacarpal tracing during circumduction task, fit to a plane to maximize the area enclosed in the shape by a) a young healthy and b) an older osteoarthritic participant. Axes are dictated by the plane fit of data.

Functional abduction

Functional adduction-abduction, was defined as a hand position that one would use if going to pick up a large diameter drinking glass – spreading their thumb and index finger far apart. The range of motion was calculated the same way as palmar adduction-abduction (using marker placed on the second MCP, radial styloid, and proximal phalange of the thumb) however the motion is on an oblique plane.

3.3.4 VAS pain scores

A validated 100 mm VAS score was used to address the question, "during the last 48 hours, how would you describe your right thumb pain?"[192].

3.3.5 FIHOA questionnaire

Participants completed the 10 question FIHOA questionnaire with responses for each question ranging from 0 (possible without difficulty) to 3 (impossible). Possible scores range from 0 to 30. It is one of the most validated and specific hand OA questionnaires and includes questions that ask participants if they are able to perform tasks, such as fastening buttons.

3.3.6 Statistical analysis

A one-way ANOVA was used to compare trends between YH, OH, and OA groups for each motion: radial adduction-abduction, palmar adduction-abduction, metacarpophalangeal flexion alone, metacarpophalangeal extension alone, interphalangeal flexion alone, interphalangeal extension alone, opposition to the base of the fifth finger, functional adduction-abduction, and circumduction (OriginPro8, OriginLab, Northhampton, MA). Tukey post-hoc test was used to determine significant differences between specific groups. A p-value < 0.05 was considered statistically significant. Data was tested for normality and for equal variance using Shapiro-Wilk and Brown-Forsythe tests, respectively. For each comparison tested, data were normally distributed and had equal variance.

3.4 Results

To look at the effect of aging and CMC OA on CMC motion, participant groups were compared. Data were collected from 58 individuals in three groups:

1) 23 young healthy, average age 22.8 years ± 3.0 years, 12 males,

2) 11 older healthy, average age 64.7 ± 8.4 years, five males, and

3) 24 participants with CMC OA, average age 69.1 ± 5.7 years, six males.

3.4.1 Differences in standard clinical ranges of motion between groups

Thumb ranges of motion were smaller proximally than at the more distal joints. The smallest ranges of motion were at the CMC joint, followed by the MCP joint, and then IP joint (Table 3-2). As expected, YH participants generally had the greatest ranges of motions, but OA ranges were not always the smallest.

Table 3-2: Standard ranges of motion measures collected using motion capture.
Standard ranges of motion measures collected using motion capture for YH, OH and OA participants. Data is shown as group averages (standard deviation) in degrees.

Action	YH	OH	OA
Palmar adduction-abduction	46.7 (10.0)	42.3 (6.9)	43.9 (11.7)
Radial adduction-abduction	47.5 (13.2)	48.2 (6.3)	47.5 (11.5)
MCP flexion	58.4 (14.8)	54.6 (9.9)	50.8 (12.4)
MCP extension	15.0 (8.8)	14.3 (8.1)	20.0 (10.3)
IP flexion	73.8 (8.6)	54.0 (14.6)	62.0 (13.5)
IP extension	28.1 (15.7)	31.5 (11.4)	30.6 (12.5)

YH participants had greater palmar adduction-abduction than OH and OA; the range of motion in OH and OA participants was similar (YH 46.7° ± 10.0°, OH 42.3° ± 6.9°, and OA 43.6° ± 11.7°). All participant groups had a similar range of motion during radial adduction-abduction (YH 47.5° ± 13.2°, OH 48.2° ± 6.3°, and OA 47.5° ± 11.5°).

YH participants had more MCP and IP flexion ability than OH and OA participants. MCP flexion trends fit with expected literature trends with YH having the largest range of motion, followed by OH, then OA participants. IP flexion ability was significantly greater in YH than OH or OA participants (73.8° ± 8.6°, 54.0° ± 14.6, and 61.5° ± 13.7°, respectively; $p = 0.00011$ and $p = 0.00396$, respectively). Of note, OA participants had greater IP flexion range of motion than OH participants.

Individuals with OA had a greater ability to extend their MCP, compared to YH and OH participants, although this was not significant (15.0° ± 8.8°, 14.3° ± 8.1°, and 20.0° ± 10.3°, respectively; $p = 0.1680$ and $p = 0.2236$, respectively). All participant group were able to extend their IP to a similar degree (28.1° ± 15.7° YH, 31.5 ° ± 11.4° OH, and 30.6° ± 12.5° OA).

3.4.2 Multi-planar ranges of motion

Opposition

The distances participants could reach when opposing the tip of their thumb near the palmar side of the base of the fifth MCP were stratified by group. As expected, YH participants could reach the farthest (indicated by smallest distance), followed by OH, then OA participants. In fact, YH participants had greater ability to reach the base of the fifth MCP than OH and significantly greater ability than OA groups (minimum distance between tip of thumb IP and fifth MCP in YH was 47.0 mm, 52.7 mm in OH, and 55.9 mm in OA; $p = 0.1135$ and $p = 0.0007$, respectively; Table 3-3).

Table 3-3: Multi-planar ranges of motion.
Multi-planar ranges of motion for YH, OH, and OA participants. Data are shown as group averages (standard deviation).

Action	YH	OH	OA
Functional adduction-abduction (degrees)	56.0 (9.8)	55.3 (8.4)	50.9 (12.9)
Opposition (mm) (larger distance means they were further away from the target of the 5th MCP marker)	47.0 (4.0)	52.7 (5.9)	55.9 (10.5)
CMC angle during opposition (degrees)	15.0 (8.6)	18.6 (11.2)	21.8 (12.0)
MCP angle during opposition (degrees)	49.8 (11.3)	52.2 (5.9)	43.8 (9.8)
IP angle during opposition (degrees)	43.8 (13.8)	37.5 (11.3)	38.1 (11.3)
Circumduction area (mm^2)	603.4 (181.6)	537.1 (220.2)	439.3 (260.6)

OA participants had altered joint positioning during opposition. More specifically, OA participants had a greater CMC angle position (OA 21.8° ± 12.0°, OH 18.6° ± 11.2°, and YH 15.0° ± 8.6°) and smaller MCP angle position (OA 43.8° ± 9.8°, OH 52.2° ± 5.9°, and YH 49.8° ± 11.3°), compared to YH and OH participants (Table 3-3). IP angle positions were greatest in YH participants and similar, reduced IP angles were found in OH and OA participants during opposition (YH 43.8° ± 13.8°, OH 37.5° ± 11.3°, and OA 38.1° ± 11.3°).

Circumduction area

When scribing an area, YH participants were able to enclose a larger area with their first metacarpal than OH participants, and a significantly larger area than OA participants ($p = 0.7012$ and $p = 0.0400$, respectively).

Functional adduction-abduction

Interestingly, OA participants exhibited a greater deficit in functional abduction-adduction ability than in either palmar adduction-abduction or radial adduction-abduction. Compared to YH participants, OA had similar radial adduction-abduction, but reduced palmar adduction-abduction by 2.8° and reduced functional adduction-abduction by 5.1°. Functional adduction-abduction range of motion had a greater separation between group results, than could be identified from the standard clinical ranges of motion testing. YH and OH had similar abilities, while the OA participants had the smallest range of motion (YH 56.0° ± 9.8°, OH 55.3° ± 8.4°, and OA range 50.9° ± 12.9°; Table 3-3). P-values for all motions performed are in Table 3-4.

Table 3-4: Comparison of p-values between healthy groups and older groups for each motion tested, standard and multi-planar.

Standard Ranges of Motion	**P-value for YH vs. OH**	**P-value for OH vs. OA**	**P-value for YH vs. OA**
Palmar adduction-abduction	0.4781	0.9046	0.6223
Radial adduction-abduction	0.9849	0.9847	1.000
MCP flexion	0.7073	0.7040	0.1220
MCP extension	0.9772	0.2236	0.1680
IP flexion	0.0001	0.1702	0.0040
IP extension	0.7777	0.9822	0.8068
Multi-planar Motions			
Opposition distance	0.1135	0.5082	0.0007
Opposition CMC angle	0.6267	0.6873	0.0808
Opposition MCP angle	0.7877	0.0607	0.1051
Opposition IP angle	0.3529	0.9903	0.2627
Circumduction area	0.7012	0.4604	0.0398
Functional adduction-abduction	0.9835	0.5186	0.2585

3.4.3 VAS pain scores and FIHOA questionnaire responses

As expected, YH and OH participants had low VAS scores and unimpaired FIHOA scores. OA participants had significantly more pain and worse function then healthy group participants. The average VAS score in the tested thumb was significantly higher in OA participants (OA 20.6 mm (17.9), OH (0.3 mm (0.9), and YH 0.0 mm (0.0); $p < 0.001$). The average FIHOA questionnaire score was significantly larger in OA participants, suggesting that OA participants had worse function than the healthy participants (OA 5.9 (3.7), OH 0.1 (0.3), and YH 0.0 (0.0); $p < 0.001$).

3.5 Discussion

The goals of this research were 1) to determine differences in thumb motions across three groups of participants (i.e., young healthy, older healthy and those with CMC OA) and 2) to determine if multi-planar motions provided additional movement information in comparison to standard planar measures. The work presented here is one of the most comprehensive motion datasets available with a total of 58 participants. Our results demonstrate that motion capture detects changes in CMC mobility that were not detected using standard clinical approaches. This study also suggests that the early stages of OA may identifiable through multi-planar measurements, which may permit quicker therapeutic intervention.

3.5.1 Standard clinical ranges of motion

Our OA participants had a small loss in palmar abduction-adduction range of motion compared to healthy participants. Additionally, trends were observed that were not previously described in OA persons, specifically, increased IP flexion and MCP extension motions[2,73,159]. Individual joint ranges of motion for all participant groups in this study were within previously reported healthy ranges of motion[49,73,193]. However, there are some unique findings discussed next.

MCP and IP motion changes are an important part of CMC OA disease progression as many times when one joint is affected, compensation may occur in other joints. IP flexion was significantly greater in YH participants than OA and OH. Interestingly, OA had a trend of increased IP flexion when compared to OH participants. OA participants also had a trend of increased MCP extension when compared to healthy participants. When these findings are coupled together, they may in fact be precursors to development of a zigzag deformity[159,194–196]. A zigzag deformity occurs when changes at the MCP and IP joints, specifically MCP hyperextension and increased IP flexion occur *in the presence with an adducted CMC joint*[42]. This deformity occurs in persons with CMC OA and were thought to be a result of functional compensation for CMC motion deficits[159,194–196]. However, our results suggest that changes in MCP and IP motion abilities occur *prior* to CMC motion deficits, and thus they may be contributors to OA progression, not subsequent compensation for CMC changes.

Although changes in palmar adduction-abduction and radial adduction-abduction due to CMC OA are highly cited and are associated with thumb function, based on our findings, these may not be the best movements to identify the presence of early CMC OA and differentiate between healthy and OA joints. Unfortunately, MCP or IP changes alone are not suitable identifiers for motion changes associated with OA because they are not exclusive to CMC OA. For example, increased MCP extension can occur as part of CMC OA disease pathology, or in the absence of OA like in dorsal dislocation[197]. Therefore, early identifiers of CMC OA must include CMC specific changes, not distal joint changes alone.

3.5.2 Multi-planar ranges of motion

Multi-planar motions were capable of detecting early changes in motion patterns that were not able to be obtained with standard clinical measures. These multi-planar measures have not been previously reported, and based on our findings, they have the potential to identify early changes in function associated with OA. Specifically, both opposition and circumduction area were significantly affected by age and OA status. These changes were identified prior to significant loss of standard clinical CMC ranges of motion (palmar adduction-abduction and radial adduction-abduction). This suggests that these multi-planar motions may be better candidates to monitor for initial signs of loss of function due to OA than the standard clinical ranges of motion. To our knowledge, this was one of the first studies that sought to develop an approach to measure CMC motion in a more comprehensive manner by including both standard clinical ranges of motion and multi-planar motion.

Opposition

Opposition abilities were stratified by group. The reduced ability to oppose seen in OA participants may be due to alterations in joint abilities. There were trends of reduced MCP flexion and increased CMC flexion in our OA participants. These trends may be another indicator that MCP joint changes may occur earlier than thought in OA. If the MCP joint has an extended position in the OA participants, as suggested by standard clinical ranges of motion, it would be more difficult to force the joint into flexion. Because the joints of the thumb are in a chain and are influenced by each other, poor MCP flexion ability may lead to increased CMC flexion to compensate and reach during opposition[75]. Alternatively, laxity at the joints may be causing the alternation in joint alignment.

Circumduction area

Circumduction is a more comprehensive way to measure CMC motion than opposition or standard clinical ranges of motion[75,76]. The reduced area seen in OA participants compared to healthy counterparts recapitulate findings by Gehrmann et al[76]. Our work adds an older healthy group, allowing us to differentiate the effects of aging and CMC OA, and indicating that the circumduction tasks was able to separate participant groups based on the area they could scribe. This suggests that CMC OA participants may have a global reduction in CMC motion ability; there is no significant loss in standard clinical CMC ranges of motions, but there is a significant reduction to comprehensive, multi-planar circumduction, a motion that incorporates radial, palmar, and opposition movements. The OA group also had a larger standard deviation in circumduction area than healthy groups; this may be due to differences in neuromuscular control or the underlying musculoskeletal deterioration in our participants. More research is necessary to determine the impact of treatment to improve neuromuscular control and mitigate musculoskeletal changes.

Standard deviation during multi-planar tasks

In contrast to the similar standard deviations found between groups during standard clinical ranges of motion testing, during all multi-planar tasks, the OA group had a larger standard deviation in their results than either healthy group. For example, the OA participants exhibited double the standard deviation of the healthy groups during opposition. Because the standard deviation in our groups was due to inter-subject variation, not intra-subject, this may suggest that multi-planar tasks are able to detect subtle differences in motion abilities that the standard ranges of motion tested clinically cannot.

This work also brings us one step closer to understanding the full function of the CMC joint, and the transition from a healthy joint to an aging joint and from an aging joint to an osteoarthritic joint. Through initial baseline datasets for healthy ranges of motion, both for the younger and older individuals, and for an OA group, this study lays the foundation for future work. Further use of these methods to identify early motion changes associated with CMC OA are likely to lead to the development of better treatments and patient care.

In the future, simple clinical devices using a basic set of cameras, inexpensive motion system, or a set of sensors could be developed to monitor the complex multi-planar motions rather than having clinics use a research-based motion capture system. Identification of early changes in motion patterns will enable providers to note motion difficulties earlier and prescribe conservative therapy earlier than we is currently possible. Earlier treatment will result in reduced symptomology and mitigate disease progression.

3.5.3 VAS pain scores and FIHOA questionnaire responses

The OA participant VAS and FIHOA scores reported here are associated with mild OA symptomology[111,118,130,192,198–200]. These scores suggest our OA participants were less impaired and had less pain than those included in other OA studies[111,118,130,192,198–200]. This is in line with our reduced CMC motion trends. This also confirms that multi-planar motion deficits occurred in participants with mild symptomatology—prior to moderate pain or perceived functional deficit. 3D motion tracking may be more valuable in early OA than pain or FIHOA tracking.

3.5.4 Limitations

Although this study includes a relatively large sample for motion capture methodology, these results are limited by our participant populations and sample size. More specifically, opposition distance, CMC angle, and MCP angle during opposition, all had near significant p-values (p =

0.06-0.12) and medium effect sizes, suggesting that more participants would yield statistical significances between groups. Increased recruitment of older, healthy participants would strengthen our understanding of the motion changes associated with OA and how they differ from motion changes due to aging alone. However, this population was challenging to recruit as participation incentives were less motivating to the OH population.

These findings are not directed to suggest that every clinic and rehab facility should use motion capture to evaluate CMC motion. Rather, we want to illustrate that motion capture is capable of measuring distinct and specific CMC motions and deviations in movement ability. Once these abilities and differences have been confirmed, the next goal will be to develop simple devices that can be employed in a clinically setting (and at home) to obtain these specific multi-planar motion measurements.

CHAPTER 4: THE EFFECTS OF SHORT-TERM HAND EXERCISES ON THUMB FUNCTION IN PARTICIPANTS WITH CARPOMETACARPAL OSTEOARTHRITIS

4.1 Abstract

Although exercise is a part of carpometacarpal osteoarthritis treatment, exercise therapy prescription is limited by the lack of evidence-based research supporting its benefits. In order to improve treatments, the evidence basis for exercise therapy using quantifiable measures like range of motion must be researched in more depth. Although considered the gold standard for measuring motion clinically, goniometer has high variability when measuring carpometacarpal motion, particularly with individuals who have hand osteoarthritis. Motion capture on the other hand, is one such method that can be used to obtain both standard clinically measured carpometacarpal ranges of motion and complex multi-planar motions, with more accuracy than a goniometer. Capturing standard clinical and multi-planar motion datasets can reveal new motion trends and lead to a greater understanding of joint function. The goal of this research was to identify changes in carpometacarpal motions as a result of a six-week exercise regimen. These changes were determined through two approaches 1) standard goniometry measures and 2) complex movements measured through the use of a motion capture system.

Although six weeks of exercise were sufficient to improve standard clinical ranges of motion using goniometry and produce trends of improvement using motion capture, it was not sufficient to demonstrate changes in the complex motion activities. However, specific task-oriented exercises that were practiced daily as part of the exercise regimen led to significant changes in thumb posture when reproducing these motions. Task-oriented exercises may produce greater benefits than those focused solely on range of motion, and should be considered when developing exercise regimens.

4.2 Introduction

Osteoarthritis (OA) is the most common degenerative joint disease, and in 50% of those over the age of 65, the thumb carpometacarpal (CMC) joint is affected[8]. The CMC joint plays a critical role in hand and arm function, and is essential for daily tasks such as holding a pen and turning a key in a lock[1,20,42]. In severe disease, joint pain and loss of range of motion can become debilitating; affected individuals require assistive devices and may lose their ability to live independently[4,20].

Although exercise is part of CMC OA treatment, exercise therapy prescription is limited by the lack of evidence-based research supporting its benefits. More specifically, the effects of hand exercise on CMC motion and OA symptomology is unclear. Although several studies have investigated the effect of hand exercises on qualitative improvements like perceived function and pain, no published work was found from the last 20 years that has looked at the ability of hand exercises to improve ranges of motion in CMC OA participants[5,22,124,131,161,201].

In order to improve treatments, the evidence basis for exercise therapy using quantifiable measures like range of motion must be researched in more depth. In a clinical setting, standard clinical ranges of motion are quantified using a goniometer. Although the gold standard for measuring motion clinically, goniometer measures have high variability, particularly in individuals with OA[66,67,170,172,173]. Additionally, goniometry can only be used to measure motion in a single plane at a time, while the CMC joint moves in multiple planes simultaneously[55,64]. However, motion capture is one such method that can be used to measure both standard clinically measured CMC ranges of motion and complex multi-planar motions, with greater accuracy than a goniometer[65,68,69,176].

Capturing standard clinical and multi-planar motion datasets have the potential to reveal new motion trends and lead to a better understanding of joint function[1,76,182]. Motion capture data also allow for more advanced motion analyses, including calculating multiple joint angles simultaneously and evaluating shape changes in motion patterns, which allow researchers to extract additional insight from movements during testing. By identifying the specific motion benefits of exercise therapy, we will increase the evidence basis for exercise therapy in the treatment of CMC OA and provide information to help clinicians make informed treatment decisions.

The goal of this research was to identify changes in CMC motions for participants with CMC OA as a result of a six-week exercise regimen. These changes were determined through two approaches 1) standard goniometry measures and 2) complex movements measured through the use of a motion capture system.

4.3 Methods

4.3.1 Testing

Participants with doctor-diagnosed CMC OA were recruited to participant in this study. Participants were tested at three time points: *week zero* (pre-exercise), *week two* (following two weeks of stretching exercises) and *week six* (following four weeks of stretching and strengthening exercises). At each time point, motion data (using goniometry and a motion capture system), Visual Analogue Scale (VAS) for pain, and Functional Index of Hand OsteoArthritis (FIHOA) scores were collected from each participant at the same time of day. All testing was completed in accordance with the university's Institutional Review Board regulations and approvals were obtained for all testing.

4.3.2 Exercise regimens

Exercises were selected in conjunction with a hand therapist based on 43 years of clinical experience. The exercise regimen was designed to relax the contracted first web space muscles (namely adductor pollicis) and to strengthen the muscles surrounding the first metacarpal (abductor pollicis longus, abductor pollicis brevis, opponens pollicis, and first dorsal interosseous muscles; Tables 4-1 and 4-2) that are important for CMC function[101,202,203]. These exercises also engaged the wrist stabilizing muscles which were necessary to effectively use the thumb in a controlled manner[204]. This regimen included opposition and retropposition exercises to stabilize the CMC joint. In addition, the okay sign postures were designed to teach the participant to use his/her thumb with the CMC joint in a stable position, similar to the position used during protective splinting.

Following initial testing, each participant was verbally and visually instructed how to complete each exercise. The participant then completed each exercise with the instructor. Participants were asked to complete the exercises at least once per day, and were given handouts with exercise instructions as well as a DVD of the exercises. To aid with exercise tracking, participants were provided with an exercise calendar. Throughout the trial, participants were contacted periodically to remind them to complete their exercises and to answer any questions that arose.

Table 4-1: Stretching exercise regimen.
Completed one to three times daily.

Passive range of motion exercises. These stretches should be held 30-90 seconds each.	
1st Web Space Release  With the pinkie side of hand resting on table, the opposite thumb was gently pressed into the web space and the opposite index and middle finger were wrapped around the palm side of web space.	Cone Stretch  The hand was wrapped around the cone to gently relax the muscles in the first web space. A slight flex (bend) should be maintained in the distal joints.
Palmar Abduction  With the hand resting on a tabletop, the opposite thumb, index, and middle fingers were used to gently stretch the thumb across the body.	Radial Abduction  With the hand resting on a tabletop, the opposite thumb, index, and middle finger were used to gently lift the thumb away from the rest of the hand, moving it towards the body.
Bilateral Web Space Stretch  With the first web spaces intertwined between the thumbs and index fingers, the elbows were allowed to gently to fall to participant's sides, stretching the first web spaces.	
Active range of motion exercises. Three sets of 8-12 repetitions should be completed for each stretch, holding each repetition for 1-3 seconds.	
Radial Abduction  With the hand resting on a tabletop, the thumb was lifted towards the body, so the tip of the thumb pointed towards the ceiling.	Palmar Abduction  With the hand resting on a tabletop, the thumb was gently stretched across the body.
Okay Sign  An okay sign was formed by touching the tip of the thumb to the tip of the index finger. Participants focused on making an "O-shape" with each contact and maintaining a slight bend in the thumb joints.	Opposition to Base of 5th Finger  The thumb was extended out away from the index finger and the thumb was then swept across palm to reach the base of the 5th finger.
Opposition to Fingertips  The tip of the thumb was brought together with the tip of each of the fingers. Participants focused on making an "O-shape" with each contact and maintaining a slight bend in the thumb joints.	Finger Spread  Starting with the fingertips together, the fingers were then spread apart as far as possible.

Table 4-2: Strengthening exercise regimen.
To be completed one to three times daily, beginning two weeks after stretching exercises are started. Stretching exercises should be completed prior to strengthening exercises and should be continued.

<table>
<tr><td colspan="2">Resistive band exercises. Each exercise should be repeated for 3 sets of 5-15 repetitions at least once per day. Begin 3 sets of 5 repetitions. Increase to 10, then 15 repetitions, as tolerated.</td></tr>
<tr><td>Radial abduction with therapy band resistance

With the hand resting flat on a tabletop, the thumb was stretched away from the index finger, held for one second, then relaxed.</td><td>Palmar abduction with therapy band resistance

With the pinkie side of the hand resting on the table, the thumb was stretched across the body, held for one second, then relaxed.</td></tr>
<tr><td colspan="2">Putty Exercises. At least once per day, these exercises should be completed 3 times each.</td></tr>
<tr><td>Roll Putty

Putty was rolled back and forth from the wrist to the fingertips until a tube with an inch diameter is formed.</td><td>Lateral pinch

The putty “tube” was pinched along its entire length using the side of the index finger and thumb.</td></tr>
<tr><td>Pinch Grip

The putty “tube” was pinched along the length bringing the tips of the thumb, index, and middle fingers together, while a “C-shape” at the base of the thumb and a slight bend in the thumb joints was maintained.</td><td>Okay Sign

Using the tips of the thumb and index finger, the length of the putty “tube,” was pinched by forming an okay sign with each pinch. Participants focused on maintaining a “C-shape” at the base of the thumb and a slight bend in the thumb joints during this exercise.</td></tr>
<tr><td>Resisted Finger Spread

A putty doughnut was formed. Then the ends of the fingers into the center of the doughnut and spread apart.</td><td>Putty Egg

The putty was formed into an egg shape then the “egg” was gently squeezed 5-6 times, without squeezing the putty between the thumb and fingers.</td></tr>
</table>

4.3.3 Participants

All participants, age 55-80, were right-handed and tested in the dominant hand. Participants with doctor diagnosed CMC OA, symptoms in the right thumb CMC joint, no recent history of or immediate plans for hand therapy or surgery, and no hand injury, disease, or illness other than OA were necessary for study inclusion.

4.3.4 Standard ranges of motion measured clinically

4.3.4.1 Goniometry

Standard clinical ranges of motion for the thumb CMC joint were measured using a goniometer, and were taken by the same individual using the same goniometer to reduce variability between measurements during active ranges of motion (i.e. the participant actively moving the joint into its maximum range)[67]. For each measurement, the plastic arms of the goniometer were laid midline along the relevant landmark.

Radial abduction measurement

The radial abduction angle was measured with the stationary arm of the goniometer overlying the extensor digitorum tendon of the third digit (middle finger). This positioning was used to mitigate the effect of participants potentially ulnar deviating their index finger thus creating an artificially increased radial abduction angle. The mobile arm of the goniometer was placed parallel to and along the dorsal surface of the first metacarpal.

Palmar abduction measurement

To measure palmar abduction angle, the stationary arm of the goniometer was placed along the radial side of the second metacarpal while the ulnar side of the participant's hand lied flat on the table. The mobile arm was placed along the dorsoradial surface of the first metacarpal.

4.3.4.2 Kapandji index

Opposition ability was measured using the Kapandji index based on standard clinical practices[169,170,205]. Using this index, the ability of the thumb to oppose to different digits and locations of the hand were scored. A score of nine or greater (where the tip of the thumb was brought over the palmar side of the fifth MCP digit) was considered normal. Kapandji index scores served as a comparison for opposition motions measured using the motion capture system.

4.3.5 Motion capture

A seven camera Qualisys motion capture system (Gothenburg, Sweden) was used to capture motion data of the thumb and index finger. Reflective markers, seven pods of four individual markers and eight single markers, were placed on the right hand and wrist to measure thumb and index finger movement (Figure 4-1). All motions were repeated in triplicate, except circumduction which was completed five times. The averaged data for each motion was used for statistical analysis. Motion capture was also used to measure standard clinical ranges of motion: radial adduction-abduction and palmar adduction-abduction. Additionally, new multi-planar motions not typically measured in the clinic were also obtained: opposition, circumduction area, and an okay sign (Figure 4-2).

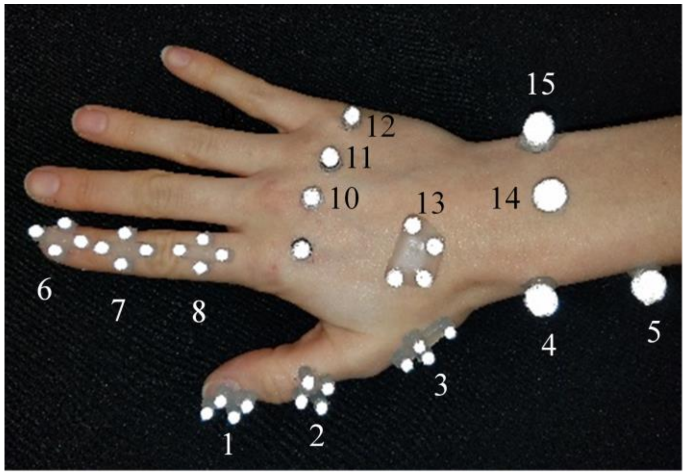

Figure 4-1: Motion capture marker placement.
Rigid four marker pods were placed on each thumb and index segment and single markers were placed on bony landmarks. Markers are as follows: 1- thumb distal phalange, 2-thumb proximal phalange, 3-first metacarpal, 4-ulnar side of radial styloid, 5-proximal radius, 6-index distal phalange, 7-index middle phalange, 8-index proximal phalange, 9- to the 2nd metacarpophalangeal joint, 10- the 3rd metacarpophalangeal joint, 11- the 4th metacarpophalangeal joint, 12- the 5th metacarpophalangeal joint, 13-palm, 14-mid-wrist (ulnar side of Lister's tubercle), and 15-ulnar styloid. For calculations, individual markers on the thumb pods, are referred to based on their locations: 1) distal most, 2) proximal most, 3) radial, and 4) ulnar.

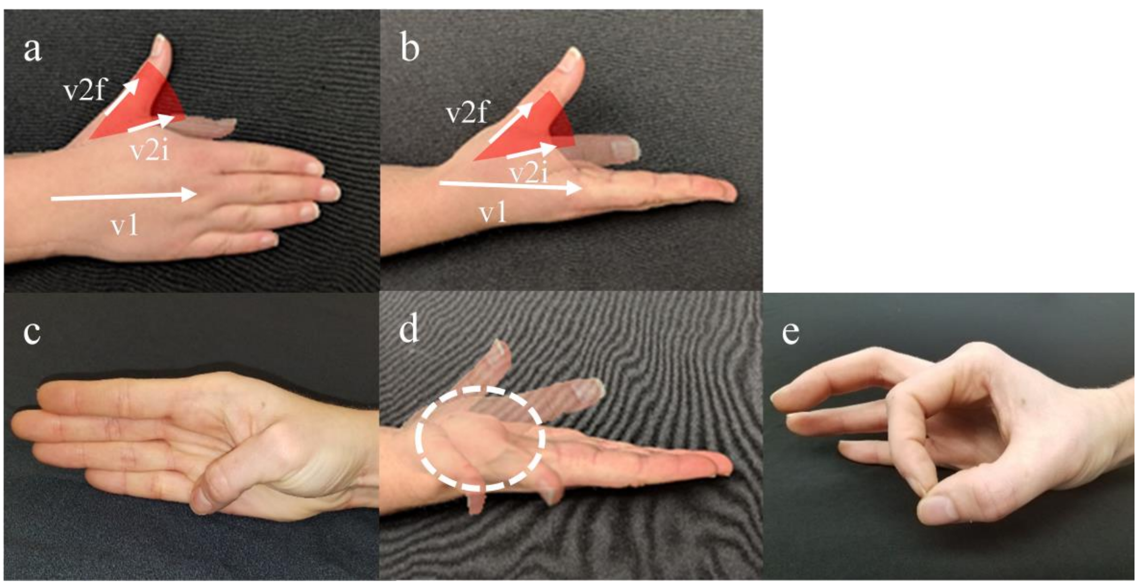

Figure 4-2: Standard clinical range of motions and multi-planar motions.
Standard clinical ranges of motion and the vectors used are shown for a) radial adduction-abduction and b) palmar adduction-abduction. Multi-planar motions tested were c) opposition, d) circumduction, and e) okay sign. The dotted circle on panel d shows the approximate path of the distal most marker of the first metacarpal.

4.3.5.1 Standard clinical ranges of motion measured using motion capture

To measure standard clinical ranges of motion, angles were obtained using the dot product between two 3D vectors, labeled 1 and 2, to determine the ranges of motion of the joints of interest (Table 4-3). Angles were measured at the start and end of each motion (Equation 1). Note that the marker placements were slightly different than the location of arm placement using goniometry; for radial adduction-abduction and palmar adduction-abduction, the first metacarpal marker was located on the dorsolateral surface of the first metacarpal rather than the dorsal surface (which is used to measure ranges of motion using a goniometer.

$$\Theta = \cos^{-1}\left(\frac{\boldsymbol{V_1} \cdot \boldsymbol{V_2}}{|\boldsymbol{V}_1||\boldsymbol{V_2}|}\right)$$

Equation 4-1

Table 4-3: Vectors used to calculate ranges of motion with vectors created from motion capture markers.

Motion/Angle Name	Vector 1 Markers	Vector 2 Markers
Radial Adduction-Abduction	third MCP—midwrist	first MCP distal—first MCP proximal
Palmar Adduction-Abduction	second MCP—radial styloid	first MCP distal—first MCP proximal
CMC angle (opposition)	radial styloid—proximal radius	first metacarpal distal—first metacarpal proximal
MCP angle (opposition)	first metacarpal distal—first metacarpal proximal	first MCP distal—first MCP proximal
IP angle (opposition)	first MCP distal—first MCP proximal	IP distal—IP proximal

4.3.5.2 Multi-planar ranges of motion using motion capture

Opposition

To measure opposition, the ability to reach the base of the fifth finger with the tip of the thumb was measured (Figure 4-2c). The minimum distance between the distal most marker on the tip of the thumb pod (distal phalange pod) and the marker on the dorsal side of the fifth MCP calculate an opposition distance. Smaller distances indicated the thumb was closer to the fifth MCP joint (better opposition ability). Equation 4-1 was used to calculate thumb joint angles (vectors shown in Table 4-3). The motion capture frame with the maximum opposition (minimum distance between the two markers) was the frame of interest and was the frame in which CMC, MCP, and IP angles were calculated during opposition.

Circumduction area

To measure circumduction area, Principal Component Analysis (PCA) was used to determine the area scribed by the distal most marker on the first metacarpal. PCA minimized the total of the distances between the positions of the distal most first metacarpal marker and a plane in three dimensions (Figure 4-2d). The total area encompassed by the projections of the marker position onto that plane was collected and was normalized to the respective individual's first metacarpal length (Matlab, Mathworks).

Okay sign

For this motion, participants were asked to form an okay sign with their fingers (thumb and index) gently touching together. To measure adjacent joint angles, the virtual center of each pod was found. The relative angle was found between the marker of interest and the adjacent markers: 1) first metacarpal and the adjacent markers for okay posture, second metacarpophalangeal joint and proximal phalange of the thumb, 2) thumb proximal phalange and adjacent markers, thumb distal phalange and first metacarpal, 3) thumb distal phalange, index distal phalange and thumb proximal phalange, 4) the second metacarpophalangeal joint, second proximal phalange and first metacarpal, 5) second proximal phalange, second metacarpophalangeal joint and second middle phalange, 6) second middle phalange, second distal phalange and second proximal phalange, and 7) second distal phalange, thumb distal phalange and index middle phalange. The area enclosed by the markers, determined by the center of each marker, was calculated (Figure 4-2e). The circularity of the space enclosed by the markers was determined by the center of each marker using Equation 2; a perfect circle would have a circularity of one. Area was calculated using a module identified as polyarea in Matlab. The hypothesis was that after completing the exercise regimen the joints would have increased flexibility, leading to an increase in circularity of the okay sign.

$$\text{Circularity} = \frac{4\pi \cdot Area}{Perimeter^2}$$

Equation 4-2

4.3.6 Clinical questionnaires

4.3.6.1 Visual Analogue Scale (VAS) pain score

For each time point, participants reported the VAS pain score for the right thumb. Scores were in reference to the perceived pain levels in the 48 hours prior to testing; a higher score indicated more pain.

4.3.6.2 Functional Index for Hand Osteoarthritis (FIHOA) score

Participants completed a modified version of the FIHOA questionnaire that asked the level of difficulty for everyday tasks like using a screwdriver. A higher score indicated more difficulty completing tasks.

4.3.7 Post-testing questionnaire

Following completion of the six weeks of exercises and testing, participants were asked a series of questions regarding specific benefits or difficulties they experienced as a result of their completion of the stretching exercises and combination (stretching and strengthening) exercises (e.g. increase/decrease range of motion, flexibility, strength, etc).

4.3.8 Statistics

To evaluate the effect of exercise, a repeated measures ANOVA with Bonferroni correction for multiple comparisons was used to compare data longitudinally. Comparisons were made for each individual motion within each measurement method (SigmaStat, Systat, San Jose, CA). For example, radial abduction using goniometry was compared at week zero to week two and to week six. For all comparisons, a p-value less than or equal to 0.05 was considered statistically significant.

4.4 Results

Of the 24 participants with OA that participated in this study (OA; average age 69.4 ± 5.8 years, six male), 21 completed all three time points (six male).

4.4.1 Standard clinical ranges of motion using goniometry and motion capture

Six weeks of exercises significantly increased radial abduction when measured through goniometry but not via motion capture ($p = 0.045$ and $p = 0.193$, respectively; Table 4-4). Goniometry measures recorded an increase in radial abduction ability at each time point.

Palmar abduction ability did not significantly increase following exercise using either measurement method. Motion capture results suggested that there may be a slight increase in palmar abduction ability following two weeks of stretching exercises, but this improvement was not maintained following combination exercises for four weeks. Following six weeks of exercise, palmar abduction ability using goniometry had an increased trend, but this was not true using motion capture; neither was statistically significant ($p = 0.123$ and $p = 0.812$, respectively).

Table 4-4: Comparison of goniometry and motion capture measurement of CMC ranges of motion prior to exercise.
Data is shown as group averages (standard deviation).

Motion	Week	Goniometry	Motion Capture
Palmar abduction (degrees)	zero	36.2 (9.4)	43.9 (11.7)
	two	35.1 (10.1)	44.8 (11.5)
	six	38.8 (7.8)	44.1 (11.0)
Radial abduction (degrees)	zero	36.8 (8.0)	47.5 (11.5)
	two	38.0 (8.0)	49.3 (11.6)
	six	40.3 (6.8)	48.1 (12.9)
Kapandji index (visually assigned score)	zero	9.0 (1.2)	-
	two	9.0 (1.2)	-
	six	9.1 (1.2)	-

4.4.2 Multi-planar ranges of motion

Opposition

Kapandji indices marginally increased following exercise, but the change was not significant (Table 4-4; OA $p = 0.555$). Similarly, opposition ability was minimally influenced by exercise when measured using motion capture (Table 4-5; $p = 0.262$). When comparing the relative role of each thumb joint's contribution to the opposition task, motion capture measurements showed that exercise significantly decreased CMC angle and produced an increased IP angle trend (CMC $p = 0.011$, MCP $p = 0.997$, and IP $p = 0.545$, respectively).

Table 4-5: The effect of exercise on multi-planar motions.
Data are shown as group average (standard deviation).

Action	Week zero	Week two	Week six
Opposition (mm)	55.9 (10.5)	53.5 (9.7)	54.1 (9.7)
Opposition CMC angle (degrees)	21.8 (12.0)	16.4 (11.6)	13.9 (6.9)
Opposition MCP angle (degrees)	43.8 (9.8)	43.9 (10.3)	42.2 (11.2)
Opposition IP angle (degrees)	38.1 (11.3)	40.1 (13.2)	43.9 (11.8)
Circumduction area (mm^2)	442.7 (261.5)	390.5 (224.7)	444.5 (276.9)
Okay sign area (mm^2)	4600.4 (643.8)	4758.2 (619.5)	4743.3 (646.9)
Okay sign circularity (one is a perfect circle)	0.859 (0.051)	0.876 (0.049)	0.872 (0.054)
Okay sign CMC angle (degrees)	70.4 (8.7)	72.3 (7.4)	72.5 (9.6)
Okay sign MCP angle (degrees)	162.8 (10.6)	154.0 (13.1)	157.7 (10.9)
Okay sign IP angle (degrees)	142.4 (8.4)	138.9 (11.9)	141.3 (7.5)

Circumduction area

The ability of participants to enclose the largest area they could using their first metacarpal was measured to further evaluate CMC motion in a more comprehensive, multi-directional manner that could be NOT obtained using goniometry or other clinical measures. However, exercise did not have an effect on the area enclosed (week zero: 442.7 mm^2 (261.5), week two: 390.5 mm^2 (224.7), and week six: 444.5 mm^2 (276.9); $p = 0.197$).

Okay sign

Following six weeks of exercise, participants increased the circularity of area enclosed in their okay sign and the area ($p = 0.081$ and $p = 0.052$, respectively). To determine if the area and circularity changes were due to changes in the posture of the thumb, joint angles were measured. Two weeks of exercise significantly increased MCP angle ($p < 0.001$). Although exercise increased the CMC angle and reduced the IP angle, these changes were not significant ($p= 0.267$ and $p = 0.219$).

4.4.3 Clinical questionnaires

Six weeks of exercise did not have an effect on pain or function as determined by self-administered questionnaires. Prior to exercise, OA participants had an average VAS pain score of 20.6 (17.9) and following two and six weeks of exercise the average scores were 24.65 (25.1) and 19.5 (17.42), respectively ($p = 0.491$). Similarly, exercise did not increase FIHOA scores (week zero 5.9 (3.7), week two 6.6 (5.5), and week six 5.5 (3.8); $p = 0.688$).

4.4.4 Post-testing questionnaires

When asked about the perceived benefits of the exercises, 2/3 of participants thought their range of motion increased, 1/2 felt more flexible and 1/3 felt less stiff following the completion of the exercise regimen.

4.5 Discussion

Although hand exercises are a recommended part of conservative CMC OA care, their motion effects have yet to be quantified in persons with CMC OA. The goal of this research was to identify changes in CMC motions as a result of a six-week exercise regimen. These changes were determined through two approaches 1) standard goniometry measures and 2) complex movements measured through the use of a motion capture system.

Although six weeks of exercise were sufficient to demonstrate significant improvements in the standard ranges of motion using goniometry and produce trends of improvement using motion capture measures for those same movements, it was not sufficient to demonstrate changes in opposition distance, circumduction area, or changes in pain or functional questionnaire scores. However, specific exercise postures that were practiced daily as part of the exercise regimen led to significant changes in thumb posture when reproducing the same motions (opposition and okay sign), following exercise.

4.5.1 Standard clinical ranges of motion using goniometry and motion capture

Although only standard clinical radial abduction improved using goniometry measures, both goniometry and motion capture measurements followed a trend of improvement. This suggests that six weeks of exercise improved CMC motion, but the degree of impact was affected by the measurement method. The difference between the two measurement methods was likely due to differences in dynamic and static movements, participant effort, and the greater accuracy of motion capture[65].

Goniometry and motion capture measurements each have different benefits and challenges to their use and assessment. Goniometry is more affordable, but restricts data collection to a single plane of motion at a time. Goniometry is the standard used in clinics, and has been for many years. Although some clinicians state that the reliability of goniometer is acceptable, clinical studies also note its poor inter-rater reliability, in particular for CMC motion[67,172,206]. However, there is less variability if the same instrument is used, and the same individual does the measurement[67]. Additionally, some goniometers have better repeatability that others[67]. In comparison, motion capture provides the ability to measure and compute components of more complex movement patterns. Because of this, it can detect the multi-planar motions necessary to assess functional tasks. Motion capture is more accurate in analyzing ranges of motion, thus we expected it to show a greater improvement to standard clinical ranges of motion than goniometry[65]. Instead, our results using motion capture indicate that exercise produced no statistical improvements for the standard clinical ranges of motion. This contrast would suggest that single planar measurements collected using goniometry may produce false positives when used to evaluate standard clinical ranges of motion. As a result, the significant change reported using goniometry should be interpreted with caution, and the clinical significance of changes documented through goniometry warrant additional study.

4.5.2 Multi-planar ranges of motion

Multi-planar motions provide a more comprehensive view of movement than single plane measures, and thus are better suited to measure the complex motions produced by the CMC joint. Here, we have shown that multi-planar motions are able to stratify participant movement abilities (chapter three), and thus we suspect, they may also provide additional insight into the effects of exercise on CMC motion than standard clinical ranges of motion. However, short-term hand exercise completion did not lead to a statistical increase in ability during opposition (opposition distance) or circumduction (change in circumduction area). This suggests that although the standard clinical range of radial abduction was improved with exercise, these benefits did not translate to improvements in the more complex movements associated with the thumb that are required during many functional activities.

Opposition is a complex task involving the sum of motion from all three thumb joints (IP, MCP, and CMC). Although a few studies have evaluated opposition ability using motion capture methods, none, to our knowledge, have done so following an exercise program[75,207,208]. Opposition distance as determined by motion capture yielded similar, but more detailed and quantitative measured (i.e., a physical distance measure) than Kapandji indices which are subjectively assessed. Opposition ability using discrete numbers, as illustrated using the opposition distance, shows greater separation between resulting values, and thus can be used to track more subtle differences. Although subtle differences may not be clinically significant, they *do* provide early cues on the effectiveness of a treatment like exercise therapy.

Motion capture opposition measures provided joint angle data than could not be obtained using Kapandji indices alone. In addition to measuring the relative location of the thumb, motion capture also allowed us to determine the contribution of each joint to the opposition task. Although this potentially could be completed with a goniometer, each joint angle must be measured independently, and it is difficult to do so, especially when measuring the CMC joint, and thus goniometry is not typically used in this manner[170]. Motion capture further allows measurements to be recorded during activity and under load, without the requisite manipulation of a goniometer. Measurement of functional activities, like opposition and okay sign, may be useful for determining the characteristics of the activity, leading to an improved understanding of overall function and everyday hand use.

Joint angles during multi-planar motions that were practiced daily as part of the exercise regimen (opposition and okay sign) were significantly altered by exercise. Following exercise, CMC flexion angle during opposition was also significantly reduced. Exercise resulted in a more extended CMC angle for OA participants, so the joint angle post-intervention was more similar to that found in young healthy participants (chapter three, Table 3-3). Increased CMC flexion was also accompanied by a trend of increased IP angle (flexion), such that the IP angle post-exercise is more similar to the IP angle in young healthy participants (chapter three, Table 3-3). Because the opposition distance was not affected by exercise, this suggests that the IP joint was bending more to compensate for the reduced contribution of the CMC joint, or the IP joint could flex more so the participants did not need to stretch the CMC joint as far to oppose the same distance. It is unclear whether this was due to a potential change in laxity at the CMC joint.

Exercise significantly changed the okay sign posture by altering joint alignment, leading to subsequent increases in area and circularity. The MCP angle was significantly increased when participants formed an okay sign motion following exercise. This was likely due to a combination of abduction and straightening of the MCP joint indicative of the practiced okay sign posture. During the initial introduction for the okay sign exercise, participants were told to stretch open their first web space, and form an okay sign while keeping a slight bend in the MCP joint. This posture was designed to activate the opponens pollicis and first dorsal interosseous muscles in order to stabilize the first metacarpal while preventing MCP hyperextension. By focusing on the shape enclosed by the thumb and index finger during the okay sign posture, joint angles increased altering the area of and the shape of the enclosed, producing trends of a more rounded (or circular) okay sign being formed and increased the area enclosed following exercise. Taken together these findings suggest that the task-oriented exercises, namely opposition and the okay sign, significantly affected thumb posture during the prescribed task.

The joint findings suggest that complex motions performed daily for the six weeks was sufficient to produce changes in thumb posture. These findings may also suggest that task-oriented motions, rather than motions solely focused on range of motion, may be more beneficial to OA participants. In other words, exercises or motions where the participant directs their attention outward (on a task in this case) rather than inward (on the muscle being used) may lead to different benefits including better balance, larger range of motion, and improved accuracy when force is applied[209–211]. These exercises should also lead to increased confidence when completing these tasks. The addition of specific more complex tasks and practicing these movements may improve joint postures and benefit participants.

The exercises employed in this study included several techniques, passive and active ranges of motion, manual medicine, and resistance exercises, as multimodal techniques have been documented to offer greater benefits to participants than singular techniques[134]. Additionally, the exercises targeted the abductor pollicis longus, abductor pollicis brevis, first dorsal interosseous, and opponens pollicis muscles to prevent first metacarpal subluxation and engage the peri-first metacarpal muscles. Many of the exercises overlap with those found in other regimens[122,125,134,212].

4.5.3 Questionnaire scores

Hand exercises did not improve the average VAS or FIHOA scores. Other hand exercise studies have shown mixed results[5,22,122–125]. Clinical questionnaire scores suggested our participants had mild pain and functional loss (average pre-exercise VAS score 20.6 and average FIHOA score 5.9), and thus there was minimal room for improvement following exercise. Other studies report pre-exercise VAS scores of 29-54 mm and FIHOA scores of 9-10[22,198,213]. This suggests that our OA group had better function than those used in other OA studies, which fits with our mild reduction in motion capture standard clinical ranges of motion results. Although we cannot rule out the chosen exercises as the cause for the lack of improvement in pain and function questionnaire scores, many of the exercises overlap with those used in other studies, some of which showed significant improvement[122,134].

Based on the post-testing questionnaire, many participants expressed a perceived benefit from the exercises including improved range of motion, flexibility, and ability to complete daily tasks. However, this was not reflected in their FIHOA scores or motion results. This may suggest that rather than a true improvement in ability, participants felt more confident in their abilities and were comfortable using their hands following exercise.

4.5.4 Limitations

One limitation of this work is that the collection of goniometry and motion capture data were not conducted simultaneously. Therefore, the possibility exists that differences in standard clinical ranges of motion between the two methods could have been due to differences in effort applied by the participants.

Another limitation is that CMC OA participants in this study presented with less severe symptomology than those enrolled in other exercise hand studies. This is illustrated by the lower average VAS and FIHOA scores in our diseased population, as well as the normal Kapandji indices. This was likely a mechanism of our recruitment criteria. In order to reduce crossover effects from other OA treatments, we recruited participants who had not and would not be seeking surgery or therapeutic treatment for their joint pain and had stable medication use. Our results may not reflect the potential for improvement in participants with severe disease; the exercises may have a greater effect on persons with more severe functional deficits, and thus is another area of research that should be investigated.

4.6 Conclusions

This study explores the therapeutic benefits of exercise for treatment of hand OA. Goniometry and motion capture have different benefits and challenges for assessment in the thumb. Improvement in standard clinical ranges of motion is not necessarily synonymous with functional improvement. Although the exercises employed here did not lead to large improvement in range of motion, they did alter joint positions. Task-oriented exercises may produce greater benefits than those focused solely on range of motion and should be considered when developing exercise regimens.

CHAPTER 5: CONCLUSIONS

Understanding of the impact of exercise on thumb force application is critical to evaluate the effectiveness of CMC OA treatment on thumb function. In this study, we successfully identified changes in thumb force generation due to short-term hand exercises in YH, OH, and OA participants. These findings support the use of the stretching and strengthening exercises to target peri-first metacarpal muscles, and as little as two weeks of stretching exercises demonstrate statistically significant changes in thumb forces in females and grip strength in males and females.

Based on this research, we can begin to observe the relationships between forces generated by the thumb and generalized hand strength. Grip strength is not predictive of changes in thumb forces; based on the data, collection of separate thumb forces are necessary to evaluate thumb function and intervention success.

To our knowledge, this study is the first to 1) compare thumb forces in healthy and OA participants and 2) investigate the effect of exercise on thumb forces in both healthy and OA participants. Understanding the effects of exercise on thumb forces will allow researchers and clinicians to better develop targeted therapies and track outcomes specific to the thumb.

Increased IP flexion and MCP extension occurred in OA participants prior to significant CMC motion deficits using standard clinical ranges of motion in participants with mild symptomatology. This finding suggests that further research is needed to investigate the sequence of motion changes that occur in the thumb of participants with OA.

We demonstrated the benefits of multi-planar measurements using motion capture to identify OA related changes to CMC mobility. Multi-planar measurements may be able to identify OA changes earlier than standard clinical approaches, allowing us to identify OA associated changes earlier, enhancing patient treatment, and reducing functional deficits. Our future work will use these techniques to evaluate the effects of therapeutic interventions on multi-planar CMC motion in CMC OA participants and healthy controls.

Chapter 4 explored the therapeutic benefits of exercise for treatment of hand OA. Goniometry and motion capture have different benefits and challenges for assessment in the thumb. Improvement in standard clinical ranges of motion is not necessarily synonymous with functional improvement. Although the exercises employed here did not lead to large improvement in range of motion, they did alter joint positions. Task-oriented exercises may produce greater benefits than those focused solely on range of motion and should be considered when developing exercise regimens.

Improved measurement capabilities are essential to improve the quality of care persons with CMC OA receive. Early diagnosis and successful therapeutic intervention are paramount to mitigate losses in motion abilities and force production. To fill the gap in the ability to quantify hand function, methods were developed to better capture thumb motions and forces.

This work contributes to the field of biomechanics by providing insight into CMC OA pathophysiology and rehabilitation. It illustrates the need to collect thumb force data and multi-planar motion data to track intervention efficacy and to develop new treatment options. These methods were able to find new, previously unreported changes, and the impact of prescribed exercise therapy on these changes. This brings up closer to understanding the impact of exercise therapy and provides insight into the benefits of 3D force and motion to evaluate disease and intervention. Future work is necessary to recapitulate these findings and to apply these methods to other treatments like splint use and surgery.

APPENDICES

APPENDIX A

IRB APPROVAL LETTERS

MICHIGAN STATE UNIVERSITY

Revision Application Approval

July 21, 2017

To: Tamara Reid-Bush
2555 Engineering Building
MSU

Re: **IRB# 17-579** Category: EXPEDITED 6, 7
Revision Approval Date: July 19, 2017
Project Expiration Date: June 6, 2018

Title: The Effect of Exercise on the Motions and Forces of the Thumb

The Institutional Review Board has completed their review of your project. I am pleased to advise you that **the revision has been approved**.

This revision includes changes to the recruitment flyer, consent forms, changes to the AUSCAN questionnaire and changes to subject incentive.

The review by the committee has found that your revision is consistent with the continued protection of the rights and welfare of human subjects, and meets the requirements of MSU's Federal Wide Assurance and the Federal Guidelines (45 CFR 46 and 21 CFR Part 50). The protection of human subjects in research is a partnership between the IRB and the investigators. We look forward to working with you as we both fulfill our responsibilities.

Renewals: IRB approval is valid until the expiration date listed above. If you are continuing your project, you must submit an *Application for Renewal* application at least one month before expiration. If the project is completed, please submit an *Application for Permanent Closure*.

Revisions: The IRB must review any changes in the project, prior to initiation of the change. Please submit an *Application for Revision* to have your changes reviewed. If changes are made at the time of renewal, please include an *Application for Revision* with the renewal application.

Problems: If issues should arise during the conduct of the research, such as unanticipated problems, adverse events, or any problem that may increase the risk to the human subjects, notify the IRB office promptly. Forms are available to report these issues.

Please use the IRB number listed above on any forms submitted which relate to this project, or on any correspondence with the IRB office.

If we can be of further assistance, please contact us at 517-355-2180 or via email at IRB@msu.edu. Thank you for your cooperation.

c: Amber Cussen

Office of Regulatory Affairs
Human Research Protection Programs

Biomedical & Health Institutional Review Board (BIRB)

Community Research Institutional Review Board (CRIRB)

Social Science Behavioral/Education Institutional Review Board (SIRB)

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MICHIGAN STATE UNIVERSITY

Modification APPROVAL

January 22, 2018

To: Tamara Reid Bush

Re: **MSU Study ID:** LEGACY17-579
IRB: Biomedical & Health Institutional Review Board (BIRB)
Principal Investigator: Tamara Reid Bush
Category: Expedited 6, 7
Submission: Modification MOD00000042
Submission Approval Date: 1/16/2018
Effective Date: 1/16/2018
Project Expiration Date: 6/6/2018

Title: The Effect of Exercise on the Motions and Forces of the Thumb

This submission has been approved by the Michigan State University (MSU) BIRB Committee.The submission was reviewed by the Institutional Review Board (IRB) through the Non-Committee Review procedure. The IRB has found that this research project protects the rights and welfare of human subjects and meets the requirements of MSU's Federal Wide Assurance (FWA00004556) and the federal regulations for the protection of human subjects in research (e.g., 45 CFR 46, 21 CFR 50, 56, other applicable regulations).

This letter acknowledges changes to eligibility criteria, research/recruitment materials, and the consent form.

Documents Approved:
• handout_highlighted change, Category: Other;
• Recruiting Flyer Hand Function YH single visit.pdf, Category: Recruitment Materials;
• Post-test questionnaire, Category: Other;
• Recruiting Flyer Hand Function YH exercise.pdf, Category: Recruitment Materials;
• Exercise Handout - match language, Category: Other;
• jan2018_HRP-510 - Template - Legacy Protocol_completed.docx, Category: IRB Protocol;
• Consent for YH participants 8Jan2018 no hightlight.pdf, Category: Consent Form;

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Continuing Review: IRB approval is valid until the expiration date listed above. If the research continues to involve human subjects, you must submit a Continuing Review request at least one month before expiration.

Modifications: Any proposed change or modification with certain limited exceptions discussed below must be reviewed and approved by the IRB prior to implementation of the change. Please submit a Modification request to have the changes reviewed. If changes are made at the time of continuing review, please submit a Modification and Continuing Review request.

Immediate Change to Eliminate a Hazard: When an immediate change in a research protocol is necessary to eliminate a hazard to subjects, the proposed change need not be reviewed by the IRB prior to its implementation. In such situations, however, investigators must report the change in protocol to the IRB immediately thereafter.

Reportable Events: Certain events require reporting to the IRB. These include:

- Potential unanticipated problems that may involve risks to subjects or others
- Potential noncompliance
- Subject complaints
- Protocol deviations or violations
- Unapproved change in protocol to eliminate a hazard to subjects
- Premature suspension or termination of research
- Audit or inspection by a federal or state agency
- New potential conflict of interest of a study team member
- Written reports of study monitors
- Emergency use of investigational drugs or devices
- Any activities or circumstances that affect the rights and welfare of research subjects
- Any information that could increase the risk to subjects

Please report new information through the project's workspace and contact the IRB office with any urgent events. Please visit the Human Research Protection Program (HRPP) website to obtain more information, including reporting timelines.

Prisoner Research: If a human subject involved in ongoing research becomes a prisoner during the course of the study and the relevant research proposal was not reviewed and approved by the IRB in accordance with the requirements for research involving prisoners under subpart C of 45 CFR part 46, the investigator must promptly notify the IRB.

Site Visits: The MSU HRPP Compliance office conducts post approval site visits for certain IRB approved projects. If the project is selected for a site visit, you will be contacted by the HRPP Compliance office to schedule the site visit.

For Projects that Involve Consent, Parental Permission, or Assent Form(s):

Use of IRB Approved Form: Investigators must use the form(s) approved by the IRB and must typically use the form with the IRB watermark.

Copy Provided to Subjects: A copy of the form(s) must be provided to the individual signing the form. In some instances, that individual must be provided with a copy of the signed form (e.g. projects following ICH-GCP E6 requirements). Assent forms should be provided as required by the IRB.

Record Retention: All records relating to the research must be appropriately managed and retained. This includes records under the investigator's control, such as the informed consent document. Investigators must retain copies of signed forms or oral consent records (e.g., logs). Investigators must retain all pages of the form, not just the signature page. Investigators may not attempt to de-identify the form; it must be retained with all original information. The PI must maintain these records for a minimum of three years after the IRB has closed the research and a longer retention period may be required by law, contract, funding agency, university requirement or other requirements for certain projects, such as those that are sponsored or FDA regulated research. See HRPP Manual Section 4-7-A, Recordkeeping for Investigators, for more information.

Closure: If the research activities no longer involve human subjects, please submit a Continuing Review request, through which project closure may be requested. Human subject research activities are complete if data collection is complete and there is no further interaction or intervention with human subjects, and analysis of identifiable private information is complete.

For More Information: See the HRPP Manual (available at https://hrpp.msu.edu/msu-hrpp-manual-table-contents-expanded).

Contact Information: If we can be of further assistance or if you have questions, please contact us at 517-355-2180 or via email at IRB@ora.msu.edu. Please visit hrpp.msu.edu to access the HRPP Manual, templates, etc.

Expedited Category. The project involves only procedures listed in Expedited Category(ies) 6,7. Please see the appropriate research category below for the full regulatory text.

Expedited 1. Clinical studies of drugs and medical devices only when condition (a) or (b) is met.
(a) Research on drugs for which an investigational new drug application (21 CFR Part 312) is not required. (Note: Research on marketed drugs that significantly increases the risks or decreases the acceptability of the risks associated with the use of the product is not eligible for expedited review.)
(b) Research on medical devices for which (i) an investigational device exemption application (21 CFR Part 812) is not required; or (ii) the medical device is cleared/approved for marketing and the medical device is being used in accordance with its cleared/approved labeling.

Expedited 2. Collection of blood samples by finger stick, heel stick, ear stick, or venipuncture as follows:
(a) from healthy, nonpregnant adults who weigh at least 110 pounds. For these subjects, the amounts drawn may not exceed 550 ml in an 8 week period and collection may not occur more frequently than 2 times per week; or
(b) from other adults and children, considering the age, weight, and health of the subjects, the collection procedure, the amount of blood to be collected, and the frequency with which it will be collected. For these subjects, the amount drawn may

not exceed the lesser of 50 ml or 3 ml per kg in an 8 week period and collection may not occur more frequently than 2 times per week.

Expedited 3. Prospective collection of biological specimens for research purposes by noninvasive means.
Examples: (a) hair and nail clippings in a nondisfiguring manner; (b) deciduous teeth at time of exfoliation or if routine patient care indicates a need for extraction; (c) permanent teeth if routine patient care indicates a need for extraction; (d) excreta and external secretions (including sweat); (e) uncannulated saliva collected either in an unstimulated fashion or stimulated by chewing gumbase or wax or by applying a dilute citric solution to the tongue; (f) placenta removed at delivery; (g) amniotic fluid obtained at the time of rupture of the membrane prior to or during labor; (h) supra- and subgingival dental plaque and calculus, provided the collection procedure is not more invasive than routine prophylactic scaling of the teeth and the process is accomplished in accordance with accepted prophylactic techniques; (i) mucosal and skin cells collected by buccal scraping or swab, skin swab, or mouth washings; (j) sputum collected after saline mist nebulization.

Expedited 4. Collection of data through noninvasive procedures (not involving general anesthesia or sedation) routinely employed in clinical practice, excluding procedures involving x-rays or microwaves. Where medical devices are employed, they must be cleared/approved for marketing. (Studies intended to evaluate the safety and effectiveness of the medical device are not generally eligible for expedited review, including studies of cleared medical devices for new indications.)
Examples: (a) physical sensors that are applied either to the surface of the body or at a distance and do not involve input of significant amounts of energy into the subject or an invasion of the subject=s privacy; (b) weighing or testing sensory acuity; (c) magnetic resonance imaging; (d) electrocardiography, electroencephalography, thermography, detection of naturally occurring radioactivity, electroretinography, ultrasound, diagnostic infrared imaging, doppler blood flow, and echocardiography; (e) moderate exercise, muscular strength testing, body composition assessment, and flexibility testing where appropriate given the age, weight, and health of the individual.

Expedited 5. Research involving materials (data, documents, records, or specimens) that have been collected, or will be collected solely for nonresearch purposes (such as medical treatment or diagnosis). (NOTE: Some research in this category may be exempt from the HHS regulations for the protection of human subjects. 45 CFR 46.101(b)(4). This listing refers only to research that is not exempt.)

Expedited 6. Collection of data from voice, video, digital, or image recordings made for research purposes.

Expedited 7. Research on individual or group characteristics or behavior (including, but not limited to, research on perception, cognition, motivation, identity, language, communication, cultural beliefs or practices, and social behavior) or research employing survey, interview, oral history, focus group, program evaluation, human factors evaluation, or quality assurance methodologies. (NOTE: Some research in this category may be exempt from the HHS regulations for the protection of human subjects. 45 CFR 46.101(b)(2) and (b)(3). This listing refers only to research that is not exempt.)

Expedited 8. Continuing review of research previously approved by the convened IRB as follows:
(a) where (i) the research is permanently closed to the enrollment of new subjects; (ii) all subjects have completed all research-related interventions; and (iii) the research remains active only for long-term follow-up of subjects; or
(b) where no subjects have been enrolled and no additional risks have been identified; or
(c) where the remaining research activities are limited to data analysis.

Expedited 9. Continuing review of research, not conducted under an investigational new drug application or investigational device exemption where categories two (2) through eight (8) do not apply but the IRB has determined and documented at a convened meeting that the research involves no greater than minimal risk and no additional risks have been identified.

Appendix B

Circumduction Matlab Codes

CircleScriptRunner

```
matfiles = dir('*.mat');
tic;
for file = matfiles'
    [~,name,~] = fileparts(file.name);
   MCircleV3(file.name)
end
toc
```

MCircle

```
function [] = MCircleV3(action)

%% Code Summary
%   1. Individual Circle Revolutions are identified using MaxMinAngle
%   Function
%   2. Plane is fitted and drawn to individual revolutions and overall for
%   the action.  This is accomplished using PCA (PlaneFitDraw)
%   3. Circle is Projected onto maximized 2D Plane for each revolution,
%   area is calculated.  (Circle Project)
%   Also includes a superimposed plot to compare each revolution plane, as
%   well as an Excel Output block.

%% Code Options - Change from 0 -> 1 to turn on each option
tic; %Starts function timer, checks to see how long to execute function
%close all %Makes it so not too many plots stay open, comment out if needed
FigOn = 1; %Max/Min Figures
PlanePlot = 0; %Plane Plots
CirclePlot = 1; %Circle Plots
ScaledPlot = 0; %Scaled Plots, show circular and square
SuperPlot = 1; %Superimposed Planes Plot
SavePlots = 1; %This saves the plots, turn off for faster code runtime
ExcelWrite = 0;
no_peaks = 11; %Change this to smaller number if needed...

%% File Open and Import - Reads filename -> action and sets import structure
FileExt = '.mat'; %This is the extension of the matlab file
ActionStr = char(strcat(action,FileExt)); %Add the extension to the action
```

```
A = importdata(ActionStr); %Import the File, aka Load it
Trajectories = A.Trajectories.Labeled.Data; %Shorthand for Traj. calls
% Rotations = A.RigidBodies.Rotations; %Shorthand for Rot. Mat. calls

%% Marker Assignment - Change Marker to CMC, T2, or DIP for different calcs
   % Note: Each marker is a matrix of position (x,y,z) in each
   % column and each row representing a frame as a unit of time
rad_sty=squeeze(Trajectories(30,1:3,:)); %30 us. 45,46  if virtual
prox_rad=squeeze(Trajectories(32,1:3,:)); %32 us. 46,47 if virtual
CMC=squeeze(Trajectories(5,1:3,:)); % us 5. if virtual 45
T2=squeeze(Trajectories(9,1:3,:));
DIP = squeeze(Trajectories(13,1:3,:));
% Had to add this to get the code to run for 1_2 CW BIG file.  Not sure why
% it is only an issue with this file... but should work now.
rad_sty(isnan(rad_sty)) = 0;
prox_rad(isnan(prox_rad)) = 0;
CMC(isnan(CMC)) = 0;
% These are the new markets of interest to calc the orientation of the palm
Palm_UL = squeeze(Trajectories(1,1:3,:));
Palm_UR = squeeze(Trajectories(2,1:3,:));
Palm_LL = squeeze(Trajectories(3,1:3,:));

Marker1 = CMC; %This assigns the Marker of Interest for the analysis

% Take the position of the marker relative to the rad_sty.
% This method eliminates some of the wobble and fits actual area w/in
% the idealized "possible area"
Marker = Marker1 - rad_sty;
Palm1 = Palm_UL - rad_sty;
Palm2 = Palm_UR - rad_sty;
Palm3 = Palm_LL - rad_sty;
%% Max/Min Angles for Marker of Interest
   % This function finds the frames that represent the start of each
   % rotation. This is used to segment the data by each individual
   % revolution and is used in later calculations.
[CircleStart] =
MaxMinAngleV3(action,Marker,prox_rad,rad_sty,FigOn,SavePlots,no_peaks);
%Now we just grab the Second Column: The Start Frames for each rotation
CircleStartList = CircleStart(:,2);

%% Fit Plane to Circles Drawn - Also find centroid of circle and plane normal
   % Function that fits a plane to each circle and plots as a figure. Plane
   % fitting is accomplished using the built in PCA function.

[Centroids,Normals,CentroidAngles,XBasisVectors,YBasisVectors,DigitMags]...
   = PlaneFitDrawV3(action,CircleStartList,Marker,PlanePlot,SavePlots);
```

```
    %DigitMags %Quick check to look at digit mags
    %% 2D Circle Projection and Circle Area Calculations
       % Here we use the data collected from the PCA analysis to project the
       % 3D data on to the plane of maximum area.  We can then use this 2D
       % projection and polyfill to find the area of the circle in mm^2.

    [CircleAreaList,ScaledAreaCirc] = CircleProjectV3...
       (action,CircleStartList,Marker,Centroids,Normals,XBasisVectors,...
       YBasisVectors,DigitMags,CirclePlot,ScaledPlot,SavePlots);

    %% Superimposed Plane Plotting - Used to Compare Consistency of Plane
    if SuperPlot == 1
       figure
       for i = 1:length(Centroids)

plot3(Centroids(i,1),Centroids(i,2),Centroids(i,3),'ro','markersize',5,'markerfacecolor','red');
          hold on
          [P,Q] = meshgrid(-15:15); % Provide a gridwork
          X = Centroids(i,1)+XBasisVectors(i,1)*YBasisVectors(i,1)*Q; % Compute the
corresponding cartesian coordinates
          Y = Centroids(i,2)+XBasisVectors(i,2)*P+YBasisVectors(i,2)*Q; % using the tbasiso
vectors in basis
          Z = Centroids(i,3)+XBasisVectors(i,3)*P+YBasisVectors(i,3)*Q;
          surf(X,Y,Z,'facecolor','blue','facealpha',0.5) %Plots the plane
          hold on
       end
       view(Normals(5,:)) %Change this to change the default view
       PlotTitle = strcat(action,'AllPlanes');
       PlotTitle = strrep(PlotTitle,'_',' ');
       title(PlotTitle)
       PlotName = strcat(action,'AllPlanes','.fig');
       xlabel('X')%added
       ylabel('Y')
       zlabel('Z')
       if SavePlots == 1
          saveas(gcf,PlotName)
       end
    end
    %% Excel Output - Writes the Action into a SubjectNo_TimePoint File
    if ExcelWrite == 1
       %File and Tab Naming Based on File Name
       FileNameArray = strsplit(action,'_');
       ExcelFile = char(strcat(FileNameArray(1),'_',FileNameArray(2),'.xlsx'));
       PageName = char(FileNameArray(3));
       %Section for CMC Angle Output
       HeaderCMC = {'CMC Min','Frame'};
```

```
    xlswrite(ExcelFile,HeaderCMC,PageName,'A1')
    xlswrite(ExcelFile,CircleStart,PageName,'A2')
    %Section for Centroid and Normal Output - Determines the plane
    CircleNo = (1:length(Normals))';
    HeaderCircle = {'Circle No','Centroid X','Centroid Y','Centroid Z'...
        ,'Normal X','Normal Y','Normal Z','CentAngle','Digit Length'};
    xlswrite(ExcelFile,HeaderCircle,PageName,'D1')
    OutputMatrix = horzcat(CircleNo,Centroids,Normals,CentroidAngles,DigitMags);
    xlswrite(ExcelFile,OutputMatrix,PageName,'D2')
    HeaderArea = {'Raw Area','ScaledAreaCirc'};
    xlswrite(ExcelFile,HeaderArea,PageName,'M1')
    AreaOutput = horzcat(CircleAreaList,ScaledAreaCirc);
    xlswrite(ExcelFile,AreaOutput,PageName,'M2')
    %Average and SD Values for the Overall File - Start to End
    OutputAverage = horzcat(nanmean(Centroids(:,1)),nanmean(Centroids(:,2))...
        ,nanmean(Centroids(:,3)),nanmean(Normals(:,1)),nanmean(Normals(:,2))...
        ,nanmean(Normals(:,3)),nanmean(CentroidAngles),nanmean(DigitMags)...
        ,nanmean(CircleAreaList),nanmean(ScaledAreaCirc));
    xlswrite(ExcelFile,{'Average'},PageName,'D15')
    xlswrite(ExcelFile,OutputAverage,PageName,'E15')
    OutputSTD = horzcat(nanstd(Centroids(:,1)),nanstd(Centroids(:,2))...
        ,nanstd(Centroids(:,3)),nanstd(Normals(:,1)),nanstd(Normals(:,2))...
        ,nanstd(Normals(:,3)),nanstd(CentroidAngles),nanstd(DigitMags)...
        ,nanstd(CircleAreaList),nanstd(ScaledAreaCirc));
    xlswrite(ExcelFile,{'STD Dev.'},PageName,'D17')
    xlswrite(ExcelFile,OutputSTD,PageName,'E17')
    OutputVar = horzcat(nanvar(Centroids(:,1)),nanvar(Centroids(:,2))...
        ,nanvar(Centroids(:,3)),nanvar(Normals(:,1)),nanvar(Normals(:,2))...
        ,nanvar(Normals(:,3)),nanvar(CentroidAngles),nanvar(DigitMags)...
        ,nanvar(CircleAreaList),nanvar(ScaledAreaCirc));
    xlswrite(ExcelFile,{'Variance'},PageName,'D19')
    xlswrite(ExcelFile,OutputVar,PageName,'E19')
      disp('Excel Written')
end
toc;
end
```

MaxMinAngle

```
function [CircleStart] = MaxMinAngleV2(action,Marker,prox_rad,rad_sty,FigOn,SavePlots)
% Function that finds the Max/Min angles of the thumb to determine the
% start and end points of individual rotations

%% Vector Calculations
    %Using the position of the marker of interest in relation to the prox
```

```
        %rad and rad sty we can create sets of vectors that we then use to
        %caclulate the angle between the vectors.  Serves as a crude but
        %accurate representation of the start and end of each circle.
    v1 = prox_rad - rad_sty; %Vector that represents the orientation of the wrist
    v2 = Marker - rad_sty; %Vector that represents the oriention of the thumb
     Angle = atan2d(norm(cross(v1,v2)),dot(v1,v2));
     %% Find Peaks to determine starting points of revolutions
    no_peaks = 11; %This number is chosen to accurately identify 10 circles for both CW and
CCW
     %Min Peaks, this represents the start of the rotation, Angle is flipped to
    %find the minimum instead of the maximum.
    [pksfm,locsfm,~,~] = findpeaks(-Angle,'MinPeakDistance', 90, 'MinPeakProminence', .1,
'NPeaks',no_peaks);
    % Note: MinPeakDistance and MinPeakProminence may have to be adjusted for
    % individual data sets.  Check Max/Min plots to determine best values
    CMC_Min(:,1) = pksfm; %First Column of Output: these are the angle values at Min
    CMC_Min(:,2) = locsfm; %Second Column of Output: these are the start frames for each
circle
     if FigOn == 1 %Figure on setting, Plots both vector and Rot. Matrix method
        figure
        plot(-Angle) %This is the plot as seen by find peaks function
        title('CMCMin Angles')
        hold on
        plot(CMC_Min(:,2),CMC_Min(:,1),'o')
        PlotName = strcat(action,'Min.png');
        if SavePlots == 1
            saveas(gcf,PlotName)
        end
    end
    %Output to Main Function
    CircleStart = CMC_Min;
    end
```

PlaneFitDraw

```
    function [Centroids,Normals,CentroidAngles,XBasisVectors,YBasisVectors,DigitMags] =
PlaneFitDrawV3(action,CircleStartList,Marker,PlanePlot,SavePlots)
    % Function that fits a plane to each circle and plots as a figure. Plane
    % fitting is accomplished using the built in PCA function.

    %% Initialize the Output Vectors to optimize Code Runtime
    NumOfLoops = length(CircleStartList)-1; %Fixes one off to account for final entry
    Centroids = zeros(NumOfLoops,3); %Init the Centroid Matrix
    Normals = zeros(NumOfLoops,3); %Init the Normals Matrix
    CentroidAngles = zeros(NumOfLoops,1);
```

```
    XBasisVectors = zeros(NumOfLoops,3);
    YBasisVectors = zeros(NumOfLoops,3);
    DigitMags = zeros(NumOfLoops,1);
    %% Plane Fitting for Each Individual Revolution
    for i = 1:NumOfLoops
        % This is a matrix of the positions (x,y,z) in mm as a function of the
        % frames contained in the individual revolution.
        PosReltoRad = Marker(:,CircleStartList(i):CircleStartList(i+1))';
        VectorAve =
[nanmean(PosReltoRad(1,:)),nanmean(PosReltoRad(2,:)),nanmean(PosReltoRad(3,:))];
        DigitMags(i) = norm(VectorAve);
        %Use PCA Function to get the normal and basis vectors for the Circle
        [coeff,~,~] = pca(PosReltoRad);
        normal = coeff(:,3);
        basis = coeff(:,1:2);
            if PlanePlot == 1
          figure
          plot3(PosReltoRad(:,1),PosReltoRad(:,2),PosReltoRad(:,3),'r.')
          hold on
        end
        %Find the centroid of the circle
        centroid =
[nanmean(PosReltoRad(:,1)),nanmean(PosReltoRad(:,2)),nanmean(PosReltoRad(:,3))];
        if PlanePlot == 1
          %Plot the centroid
          plot3(centroid(1),centroid(2),centroid(3),'ro','markersize',15,'markerfacecolor','red');
          hold on
          %Plot the plane
          [P,Q] = meshgrid(-15:15); % Provide a gridwork for the plane to span
          X = centroid(1)+basis(1,1)*P+basis(1,2)*Q;
          Y = centroid(2)+basis(2,1)*P+basis(2,2)*Q;
          Z = centroid(3)+basis(3,1)*P+basis(3,2)*Q;
          surf(X,Y,Z,'facecolor','blue','facealpha',0.5) %Plots the plane
          hold on
          PlotTitle = strcat(action,' Circle ',num2str(i));
          PlotTitle = strrep(PlotTitle,'_',' ');
          title(PlotTitle)
          PlaneExp = strcat(num2str(normal(1)),'*','(x-
',num2str(centroid(1)),')+',num2str(normal(2)),'*','(y-
',num2str(centroid(2)),')+',num2str(normal(3)),'*','(z-',num2str(centroid(3)),') = 0');
          xlabel(PlaneExp)
          PlotName = strcat(action,'3DPlane',num2str(i),'.png');
          view(0,0)
          if SavePlots == 1
            saveas(gcf,PlotName)
          end
```

```
        end
        % Look at Posotion of Radial Styloid to Find the Centroid Angle
        RadCentVector = centroid; %Find the Vector
        %Find the Angle of the Vectors using the inverse tangent function
        CentroidAngles(i,:) =
atan2d(norm(cross(RadCentVector,normal)),dot(RadCentVector,normal));
        Centroids(i,:) = centroid;
        Normals(i,:) = normal;
        XBasisVectors(i,:) = basis(:,1);
        YBasisVectors(i,:) = basis(:,2);
       end
     %% Plane Fitting for all circles drawn
    Marker = Marker(:,CircleStartList(1):CircleStartList(end))';
    %Use PCA Function to get the normal and basis vectors for all Circles
    [coeff,~,~] = pca(Marker);
    allnormal = coeff(:,3);
    allbasis = coeff(:,1:2);
    %Plot the circle drawn in 3D Space
    if PlanePlot == 1
        figure
        plot3(Marker(:,1),Marker(:,2),Marker(:,3),'r.')
        hold on
    end
    %Find the centroid of all circles
    allcentroid = [nanmean(Marker(:,1)),nanmean(Marker(:,2)),nanmean(Marker(:,3))];
    %palm_centroid = [nanmean(Palm(:,1)),nanmean(Palm(:,2)),nanmean(Palm(:,3))];
     if PlanePlot == 1
            %Plot the centroid

plot3(allcentroid(1),allcentroid(2),allcentroid(3),'ro','markersize',15,'markerfacecolor','red');
            hold on
            %Plot the plane
            [P,Q] = meshgrid(-15:15); % Provide a gridwork for the plane to span
            X = allcentroid(1)+allbasis(1,1)*P+allbasis(1,2)*Q;
            Y = allcentroid(2)+allbasis(2,1)*P+allbasis(2,2)*Q;
            Z = allcentroid(3)+allbasis(3,1)*P+allbasis(3,2)*Q;
            surf(X,Y,Z,'facecolor','blue','facealpha',0.5) %Plots the plane
            hold on
             %This names the Plot Title and Allows for changes to filename etc.
            PlotTitle = strcat(action,'3DPlane','Total');
            PlotTitle = strrep(PlotTitle,'_',' ');
            PlotName = strcat(action,'3DPlane','Total','.png');
            title(PlotTitle)
            view(0,0)
            if SavePlots == 1
                saveas(gcf,PlotName)
```

```
        end
    end
    end
```

CircleProject

```
    function [CircleAreaList] =
CircleProjectV2(action,CircleStartList,Marker,Centroids,Normals,XBasisVectors,YBasisVectors
,CirclePlot,SavePlots)
    % Here we use the data collected from the PCA analysis to project the
    % 3D data on to the plane of maximum area.  We can then use this 2D
    % projection and polyfill to find the area of the circle in mm^2.
    NumOfLoops = length(CircleStartList) - 1; %Number of Loops
    CircleAreaList = zeros(NumOfLoops,1); %Init a Area Vector for loop
    for i = 1:NumOfLoops
      % Grab the position of the marker over a circle time range
      MarkerXYZ = Marker(:,CircleStartList(i):CircleStartList(i+1))';
      LengthOfRev = length(MarkerXYZ); %Find the number of time points
      % Grab the normal and centroid for the individual circle
      normal = Normals(i,:); %Grabs the normal for the plane of this circle
      centroid = Centroids(i,:); %Grabs the centroid of this circle
      % Initalize some vectors that we will use in the next loop.
      Proj_Pts = zeros(LengthOfRev,3); %Init the Projected Pts. Matrix
      dist = zeros(LengthOfRev,3); %Init the distance between pts and plane
      for j = 1:LengthOfRev
        dist(j,:) = MarkerXYZ(j,:) - centroid;
        Proj_Pts(j,:) = MarkerXYZ(j,:) - (dot(normal,dist(j,:))*normal);
      end
      %Init the "x" and "y" values that occur on the X/YBasisVectors
      t_1 = zeros(LengthOfRev); %x-vector for the projection
      t_2 = zeros(LengthOfRev); %y-vector for the projection
      s = zeros(LengthOfRev); % Seperation from the plane
      %This loop finds the distance along the X/Y Basis Vectors for the
      %2D Projection
      for k = 1:LengthOfRev
        t_1(k) = dot(XBasisVectors(i,:), dist(k,:));
        t_2(k) = dot(YBasisVectors(i,:), dist(k,:));
        s(k) = dot(Normals(i,:),dist(k,:));
      end
       %Plot the actual 2D projection for each revolution
      if CirclePlot == 1
        figure
        plot (t_1,t_2) %These are the actual x and y values of the projected circle
        axis([-35 35 -35 35])
        hold on
```

```
        PlotName = strcat(action,'2DProj',num2str(i),'.png');
        PlotTitle = strcat(action,'2DProj',num2str(i));
 PlotTitle = strrep(PlotTitle,'_',' ');
        area1 = polyarea(t_1,t_2);
        fill(t_1,t_2,'g') %Fill the Circle
xlabel(strcat('Area = ',num2str(area1(1))));
        title(PlotTitle)
        if SavePlots == 1
            saveas(gcf,PlotName)
        end
    end
    area = polyarea(t_1,t_2);
    CircleAreaList(i) = area(1);
end
```

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