Electronic Thesis and Dissertation Repository

7-17-2019 10:30 AM

A Novel Method for In Vivo Evaluation of Finger Kinematics for Analysis of Activities of Daily Living

Ahmed M. Tanashi
The University of Western Ontario

Supervisor
Lalone, Emily A.
The University of Western Ontario

Graduate Program in Biomedical Engineering
A thesis submitted in partial fulfillment of the requirements for the degree in Master of Engineering Science
© Ahmed M. Tanashi 2019

Follow this and additional works at: https://ir.lib.uwo.ca/etd

 Part of the Biomechanical Engineering Commons

Abstract

This thesis examines the development of a six degrees of freedom finger coordinate system that employs electromagnetic tracking to measure finger kinematics. Secondarily, this thesis validated the *in vivo* finger coordinate system using a cadaveric study, with bone fixed trackers, as the gold standard. This thesis also compares the proposed method to the clinically used technique of manual goniometry. Lastly, this thesis examines the range of motion of individuals with and without hand arthritis during various activities of daily living, performed with and with joint protection program principles. This study presents a foundation for finger kinematic evaluation for *in vivo* use and describes a methodology that will be used for larger studies to be conducted to examine finger kinematics in various clinical and functional applications.

Keywords

Summary for Lay Audience

Finger kinematics is a common measurement in biomechanics to study the motion of objects. Measuring the motion of the finger bones and joints can be complicated because the hand is made up of many bones and is used a wide variety of tasks. In this thesis, a new measurement technique was developed and can be used to measure the motion pathway of the fingers in the hands when flexing and extending the fingers, but also when the hands are being used to perform an activity of daily living. This approach is novel because it can be applied to human subjects performing functional tasks. In order to ensure that the measurement technique is accurate and reliable, several smaller validation studies were also conducted. Following this, the new method was used to examine nine everyday tasks performed by both healthy participants and participants with hand osteoarthritis. Both groups performed the tasks normally and with a clinically used joint protection method. Joint protection programs are recommended to patients who have hand arthritis as they can reduce pain in the joints. However, no quantitative data exists as to their effectiveness, and they have not been updated to reflect current technology. A comparison between the recorded range of motion during these tasks was done.

In this study, the newly developed finger kinematic measurement technique is found to be comparable to finger kinematics measured clinically and is consistent with what is already presented in the literature. In terms of the clinical data, this study showed that the participants with hand osteoarthritis had less total range of motion (flexion/extension) in many of their joints. Participants with hand osteoarthritis also had less range of motion during some tasks in some of their joints. These findings are important as they show that individuals with hand osteoarthritis do perform tasks differently, and that they do have a more limited range of motion in their finger joints. It also shows that while some joint protection recommendations do decrease the range of motion, not all of them do, which may mean that these recommendations need to be updated.

This research has impact on the study of finger motion in people. Having a way to measure finger motion that is applicable to everyday tasks is important and is the foundation for many more potential studies on finger motion and diseases.

Co-Authorship Statement

Chapter 1: Ahmed Tanashi – sole author; Emily Lalone – reviewed manuscript

Chapter 2: Ahmed Tanashi – concept and design of study, acquisition of data, data analysis, interpretation of data, drafting of written document; Emily Lalone – concept and design of study, interpretation of data, reviewed manuscript; Louis Ferreira – concept and design of study, interpretation of data; O. Remus Tutunea-Fatan – concept and design of study; Mike Szekeres – concept and design of study

Chapter 3: Ahmed Tanashi – concept and design of study, acquisition of data, data analysis, interpretation of data, drafting of written document; Emily Lalone – concept and design of study, interpretation of data, reviewed manuscript; Louis Ferreira – concept and design of study, interpretation of data; O. Remus Tutunea-Fatan – concept and design of study; Mike Szekeres – concept and design of study

Chapter 4: Ahmed Tanashi – sole author; Emily Lalone – reviewed manuscript

Acknowledgments

Table of Contents

List of Tables

List of Figures

List of Appendices

Symbols and Acronyms

°	Degree(s)
%	Percentage
1D	One dimensional
2D	Two dimensional
3D	Three dimensional
4DCT	Four-dimensional computed tomography
Abd/Add	Abduction/adduction motion direction
ADL	Activities of daily living
ANOVA	Analysis of variance
CI	Confidence interval
CMC	Carpometacarpal
CT	Computed tomography
DIP	Distal interphalangeal
DoF	Degrees of freedom
EM	Electromagnetic
Flex/Ext	Flexion/extension motion direction
Int/Ext	Internal/external rotation motion direction
IP	Interphalangeal
JPP	Joint protection program
MCP	Metacarpophalangeal
mm	Millimeter(s)
MRI	Magnetic resonance imaging
H-OA	Hand Osteoarthritis
OA	Osteoarthritis
PIP	Proximal interphalangeal
RA	Rheumatoid arthritis
RoM	Range of Motion
RMS	Root Mean Squared
SD	Standard deviation

Chapter 1

1   Introduction

The hand is an end effector to a long kinematic chain extending from the trunk, to shoulder, elbow and then to the wrist. The human hand is used to manipulate, palpate, and interact with the world around us. The hand also allows us to grasp, pinch, and manipulate all manner of objects, and is comprised of many tissue types. The hand is important in daily function and independence, with problems due to disease causing physical and psychological impact on the health of an individual. Understanding the kinematics of the fingers is of great importance when looking at function and performance of tasks. One clinical application of measurement of finger kinematics is Hand Osteoarthritis (H-OA). It affects many individuals, and with the population aging, the proportion will continue to increase. Current methods of non-invasive treatment lack quantitative data obtainable through kinematic tracking and motion capture. This chapter will describe the finger anatomy, associated kinematics, osteoarthritis, and common treatments. Methods of biomechanical tracking and types of coordinate system definition are also described. Finally, the chapter concludes with the rationale, objectives, and hypotheses for this research work.

1.1   Hand and Finger Anatomy

The anatomy of the hand can be broadly grouped into that of the wrist, long fingers, and thumb. Within this document, the focus is entirely on the fingers, so these will be described in detail. The fingers consist of 19 bones, which make up the five digits (Figure 1). There are five metacarpals, five proximal phalanges, four middle phalanges (the thumb does not have one), and five distal phalanges[1]. The most proximal bones are metacarpals, and proceeding distally are the proximal, middle, and distal phalanges. The joints of the long fingers are located at the interface between each bone and are (from most proximal to most distal) the metacarpophalangeal (MCP), proximal interphalangeal (PIP), and distal interphalangeal (DIP) joints. The main joints of interest in the thumb are the carpometacarpal (CMC), metacarpophalangeal (MCP), and interphalangeal (IP) joints[1,2].

All discussed joints have articular cartilage that provides the gliding surface between joints that allows for smooth and pain free motion (Figure 2).
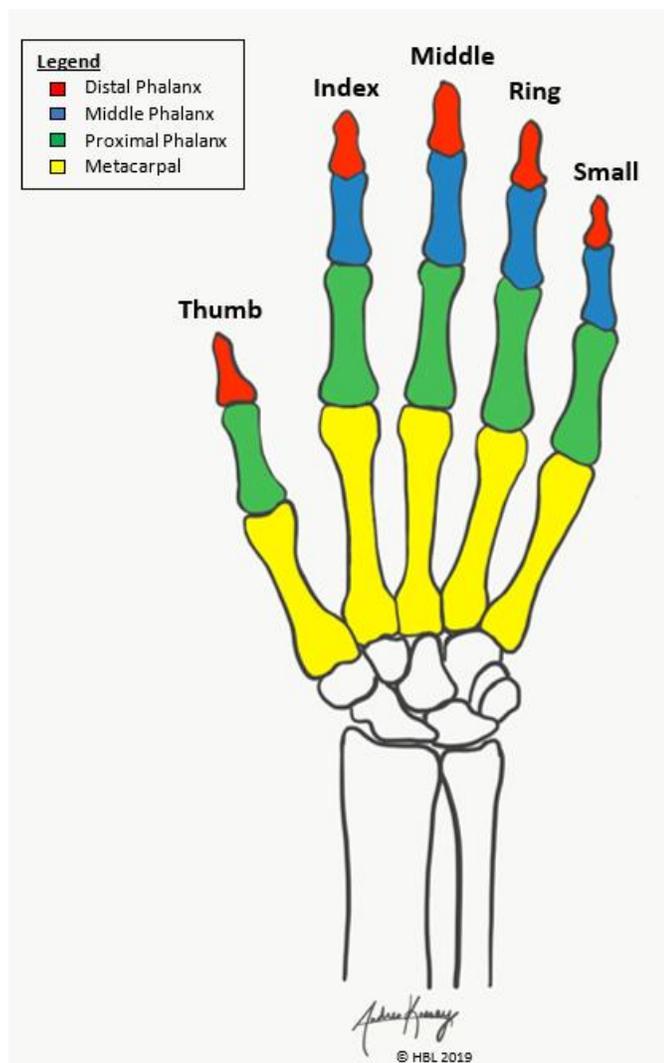
Figure 1: Hand bone locations
The bony segments of the hand: the metacarpals are in the palm of the hand (yellow), the proximal phalanges are distal to them (green), with the middle phalanges more distal (blue), and finally the distal phalanges are the most distal bones of the fingers (red). The thumb does not contain a middle phalanx.
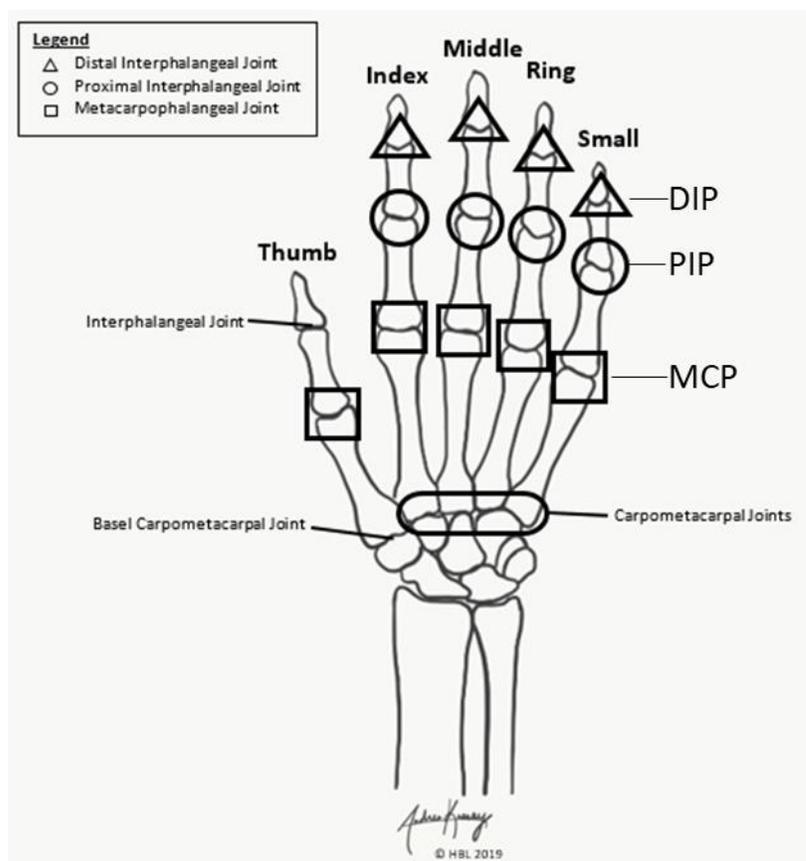
Figure 2: Joints of the fingers
The joints of the fingers: The carpals and metacarpals articulate, forming the carpometacarpal (CMC) joints. The metacarpals and proximal phalanges form joints termed the metacarpophalangeal (MCP) joints. The proximal and middle phalanges form the proximal interphalangeal (PIP) joints. The middle and distal phalanges form the distal interphalangeal (DIP) joints.

There are many soft tissues that surround and interact with the bones of the fingers. The joints of the fingers have collateral ligaments that serve to connect the bones across the joint, mostly present on the palmer and medial/lateral sides of the joint (Figure 3). There are also annular and cruciate pulleys that run along the palmer side of the fingers and insert into the distal phalanx. These pulleys keep the tendons that run along the palmar side of the hand close to the bone. Intrinsic muscles in the hand include the muscles of the thumb responsible for abduction, flexion, and opposition (abductor pollicis brevis, flexor pollicis brevis, and opponens pollicis) and adduction (adductor pollicis transverse and oblique heads) (Figure 4). The lumbricals are muscles that originate on the radial aspect of the flexor digitorum profundus and insert into the extensor expansions (palmar side). The dorsal and volar interossei are the muscles in the palm of the hand responsible for abduction

and adduction (respectively) of the fingers. The phalanges have no muscles within them, instead having tendons that attach them to muscles in the forearm (Figure 5). The extrinsic muscles on the palmer side of the forearm responsible for flexion are the flexor digitorum profundus and flexor digitorum superficialis. The extensor digitorum is the muscle primarily responsible for extension of the fingers, located in the dorsal side of the forearm[1].

Collateral ligaments

©HBL 2019
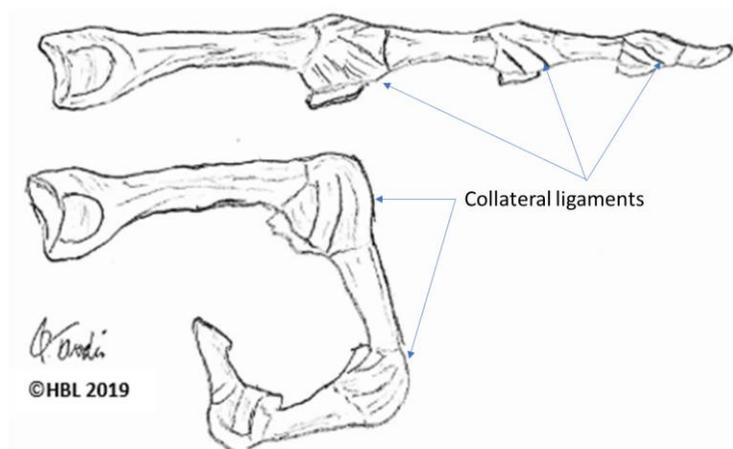
Figure 3: Collateral ligaments of the finger joints
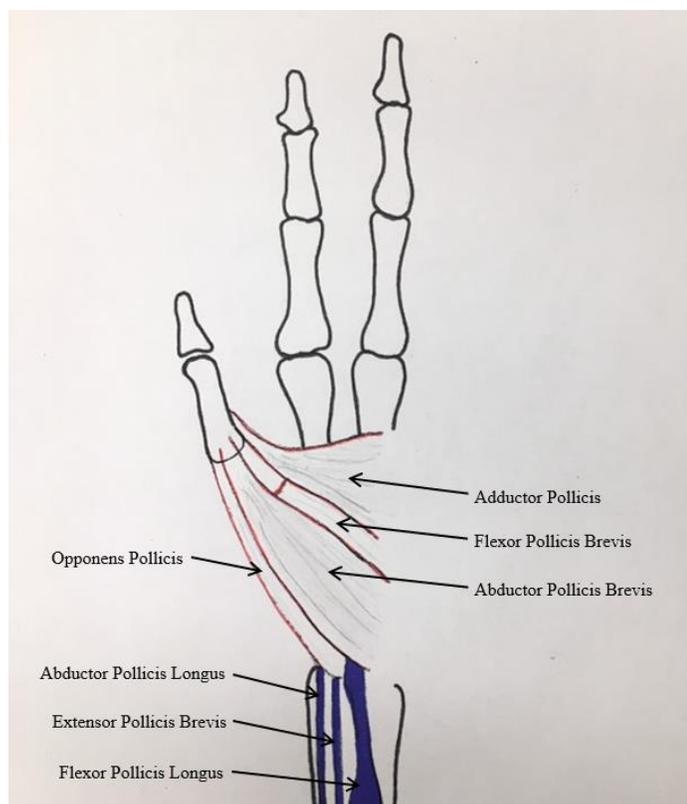
Figure 4: Major intrinsic muscles for finger and thumb motion
The muscles of the hand: the adductor pollicis, flexor pollicis brevis, abductor pollicis brevis, abductor pollicis longus, and opponens pollicis contribute to the Abd/Add motion of the thumb. The extensor pollicis brevis and flexor pollicis longus contribute to the thumb Flex/Ext motion.
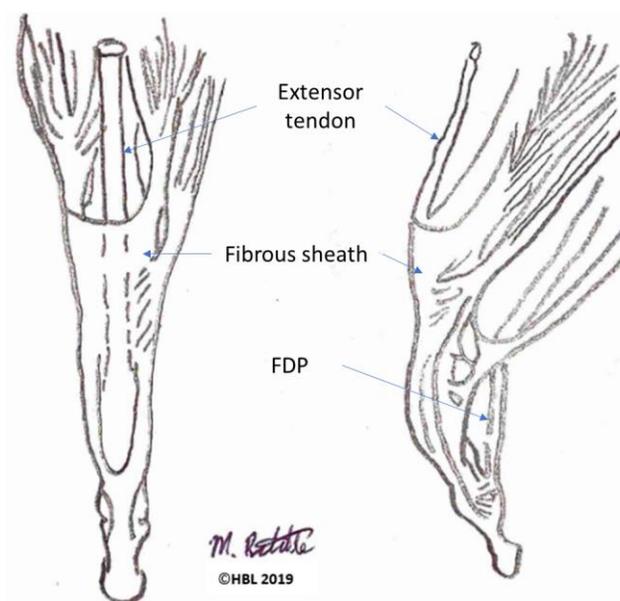
Figure 5: Soft tissues surrounding the finger
A selection of soft tissues surrounding the bony anatomy of the finger include the extensor tendon, the fibrous sheath surrounding the fingers, and the flexor digitorum profundus (FDP).

1.2   Finger Kinematics

The joints of the fingers are hinge joints, with the active motion produced being that of flexion (bringing the finger segments toward the palm) and extension (bringing the segments away from the palm) (Figure 6). The exception to this joint type is the thumb CMC joint, which is classified as a saddle joint (Figure 7), and allows for active abduction and adduction of the thumb[2,3]. These joints are true hinges, as there is a small amount of joint laxity, allowing for small amounts of lateral (Abd/Add) and axial (Int/Ext) rotation[4].
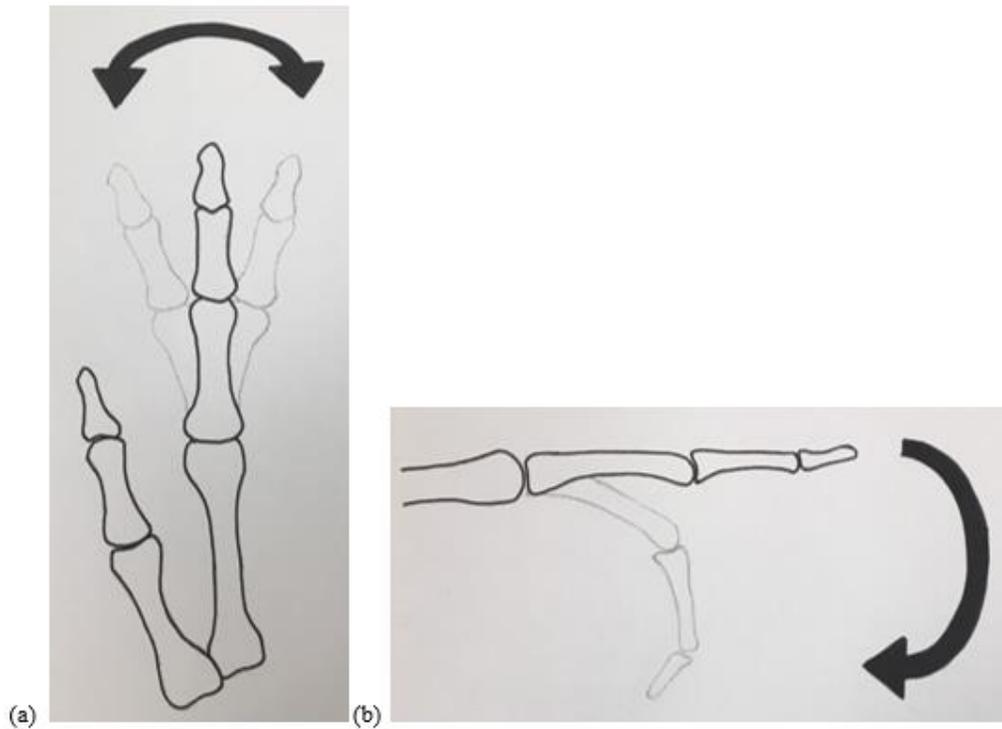
Figure 6: Finger segments range of motion capabilities
The (a) MCP joint for radial and ulnar deviation, and (b) DIP, PIP, and MCP joints for flexion/extension (lateral view).
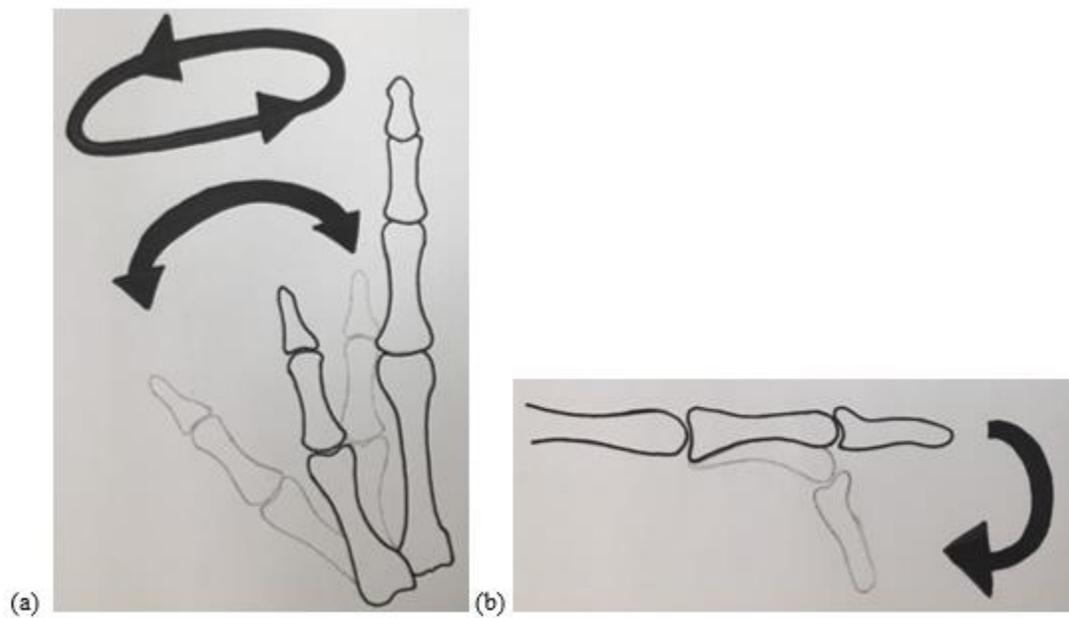
Figure 7: Thumb segment range of motion capabilities
The (a) basal CMC joint for flexion/extension, radial/ulnar deviation, and circumduction and (b) IP and MCP joints for flexion/extension.

1.3   Coordinate Systems and Definitions in Biomechanics

To track the motion of an object, it is necessary to have a way of describing its position and orientation (pose) in space with respect to other objects or references. This is commonly done in biomechanics using a coordinate system and describing the motion of the object based it. The cartesian coordinate system is used in biomechanics, describing the movement in terms of translations and rotations about three orthogonal axes. Coordinate systems are attached to rigid bodies, with bones being considered rigid bodies in most biomechanics applications.

Functional Frames

A functional frame is a frame definition that can be used in applications that involve joint motion. This type of frame has an axis aligned with the joint functional axis, or axis about which it rotates[5].

Landmark (Anatomical) Frames

A commonly used method of examining biomechanics, landmarks are used for local definition (individual bones, such as the metacarpal) of coordinate systems. This method is defined using palpable (typically bony) landmarks to create a coordinate frame that generally follows the global anatomical reference planes (frontal, sagittal, and transverse)[5]. These local definitions are used to compare the relative motion of one bone to an adjacent one, thus tracking the motion across the joint in question. Since this method typically uses bony landmarks, it is commonly used in *in vitro* test settings, where access to the bones is relatively easy. A unique advantage to using anatomical frames was highlighted by Goislard de Monsabert *et al.* stating that landmark definitions are applicable to cases of finger deformity or compromised joint motion[5].

Reference Frames

A reference frame definition is another approach to create coordinate systems used for kinematic analysis and in biomechanical assessment. This frame definition involves aligning the frame created with an external reference frame, external to the system being

examined. This is typically done in a static postural pose. This approach is similar to landmark frames in the sense that landmarks on the bony segments must still be digitized[5]. This type of definition can report results that are not physiologically relevant, and this can be seen in joints with multiple DoF[5].

1.4 Quantifying Finger Kinematics

There are many barriers in evaluating and quantifying finger kinematics. The fingers themselves are made up of many small rigid bodies, and associated degrees of freedom. Additionally, the fingers themselves are narrow and provide a very limited amount of surface area for attaching sensors to. Skin motion artifact may also be significant as the skin can be lax. The range of motion of the fingers is quite large compared to the size of the segments. This skin motion obscures the underlying bone kinematics in in vivo measurement[6]. Fingers also allow for the dexterous manipulation of objects and are what allow for execution of precise tasks and complex functions. This results in the fingers having very complex motion pathways that are difficult to capture[7].

1.4.1 Finger Kinematics

One very prominent resource for defining finger kinematics and the associated frames is the International Society of Biomechanics (ISB). Specific joint coordinate systems for reporting a variety of joints in the upper extremity has been proposed[8]. In this previously developed coordinate system, the origin of the metacarpal coordinate system is defined as the location midway between the center of the head and base of the bone, at the center of the tubular section of the bone. The Y-axis is defined as the line parallel to the line from the center of the distal head to the midpoint of the metacarpal. The X-axis is defined such that the X-Y plane creates a sagittal plane that splits the metacarpal bone into mirror images. Finally, the Z axis is defined as the common perpendicular to the X and Y planes[8]. The coordinate systems for the remaining finger segments (phalanges) are created analogous to those of the metacarpal. This coordinate system definition requires bony landmarks that are not palpable *in vivo,* limiting its applicability.

Previous studies have examined the active RoM of the finger joints. Coupier *et al* (2016) reported kinematics of the long fingers and thumb[9]. They reported Flex/Ext values of Flex/Ext values of 64-114°, Abd/Add of 9-27°, and Int/Ext of 8-20° for the Flex/Ext motion of the long fingers. For the thumb, they reported Flex/Ext values of 59° for the MCP and 83° for the IP joint for the Flex/Ext motion of the thumb. One limitation noted in this study was the presence of skin motion. Carpinella *et al* reported values of 90-109° for Flex/Ext of the long fingers[10]. They used passive optical trackers, examined five static postures, and did not consider the thumb. Bain *et al.* examined the active RoM of the long fingers in total Flex/Ext motion, and found values of 109° (MCP), 108° (PIP), and 90° (DIP) using a manual goniometer[11]. The measurement method used meant that they could not perform continuous motion capture.

Quantification of finger kinematics in relation to functional tasks has been limited. A study by Buffi *et al.* looked to quantify the kinematics of the CMC joints, which are important for functional tasks. They used CT scans of one participant in a variety of hand positions in order to develop their model, and concluded that the fourth and fifth metacarpal has RoM in all three rotational axis[12]. The kinematics of a thumb and index finger pinch have been quantified using optical tracking. The extension mean angle range from 15-34°, abduction angle from -2-25°, and axial rotation from -1-95°[13]. Another study examined finger joint motion during a thumb and index tip-to-tip task, which reported approximate flexion extension values for the thumb TM (18-32°), thumb MCP (10-20°), thumb IP (23-33°), index MCP(40-80°), index PIP(35-55°), and index DIP(25-70°) across four participants[7]. A study looking at the thumb CMC joint reported range of motion of 11-26° during lateral key pinch[14]. Bain *et al.* examined the functional range of motion of the finger joints by examining 20 functional tasks from the Sollerman test of hand grip function. They examined only flexion/extension RoM, and found the functional envelope of motion to be 19-71° for the MCP joints, 23-87° for the PIP joints, and 10-64° for the DIP joints[11]. Metcalf *et al.* proposed a markerless motion capture system for measurement of hand kinematics for home-based assessment. This system utilized a Microsoft Kinect camera and validated their approach against an optical tracking method utilizing the VICON system on one participant. Reported maximum error was reported as 10° (MCP), 12° (PIP), and 11° (DIP)[15]. A comparison between healthy and reduced function hands was done by

Leitkam *et al*. Passive optical trackers were used on 22 healthy participants and 21 participants with self-reported doctor-diagnosed arthritis in the hand. A comparison of the RoM of each group during a set of basic motions was done, with results indicating that participants with arthritis had decreased RoM compared to healthy individuals in the MCP (5.50°), PIP (6.88°), and DIP (19.42°)[16].

Kinematic models of the hand have been developed to examine finger motion in various applications. A study by Leitkam *et al.* compared 9 healthy participants joint RoM to a computer model for all fingers of the hand. The participant joint RoM was reported as -13 to 60° for thumb MCP flexion, -28 to 100° for thumb IP flexion, -33 to 90° for index MCP flexion, -6 to 112° for index PIP flexion, -4 to 89° for index DIP flexion, -28 to 101° for middle MCP flexion, -6 to 120° for middle PIP flexion, and -2 to 97° for middle DIP flexion[17]. Sancho-Bru *et al.* proposed a dynamic model of the human finger to examine muscular forces. This model utilized optical tracking on one participant. They modelled the DIP and PIP joints as hinges, and the MCP joint as a 2DOF joint, with joint angles reported as approximately 50° (MCP), 100° (PIP), 50° (DIP), and 20° (MCP Abd/Add)[18]. A more developed application of this model was done by Sancho-Bru *et al.* to model grasping motions. The model was validated using a Cyberglove system (Cyberglove, Immersion Corp. San Jose, California, USA) while one participant grasped cylinders of different diameters. The joint angles reported for grasping one cylinder ranged from 13-20° for the MCP joints, 32-47° for the PIP joints, and 8-40° for the DIP joints[19]. Another study by Blana *et al.* utilized a kinematic model of the hand with experimentally-derived kinematics for motion control of a prosthetic hand. The model treated the fingers as rigid bodies connected by joints and simulated the formation of the letters A, B, C, and L in American Sign Language[20]. Barry *et al.* developed an index and thumb model for investigation of impairment. They created a model using 3D modelling software and validated it against cadaveric specimen force results[21], and focused more on musculature than kinematics directly.

1.4.2　Kinematics Tracking Tools

Any method of describing an objects position, orientation, or both in space may be a kinematic tracking technique. There are a multitude of methods for tracking, however in this document the most relevant methods will be described.

1.4.2.1　Goniometer

Clinically, goniometry is a common method used to measure a patient's finger RoM. It is a physical measurement tool, and joint angle is determined by aligning the arms of the goniometer across the joint in question. A study by Ellis *et al.* compared the reliability of goniometer measurement with another clinical measurement technique, composite finger flexion. For goniometry, they found that the intra-rater measurements were within 5°, and inter-rater measurements were within 9°[22].

1.4.2.2　Electromagnetic Tracking

Electromagnetic (EM) tracking in biomechanics involves the use of active-source systems. The system has a coil that produces an electromagnetic field. Sensors generally are comprised of three orthogonal magnetic sensor units, which when individually excited produce a component of the 3D vector that describes the sensors pose. This allows for estimation of the sensor location and orientation with respect to the source unit (coil)[23]. Electromagnetic tracking systems are susceptible to field distortions from metallic objects. An EM tracking system has been used for evaluation of trigger fingers and was reported as having positional accuracy of 1.8mm, and rotational accuracy of 0.5° (miniBirdTM electromagnetic tracking system, Ascension Technology Corporation, Burlington, VT, USA). Another study of knee kinematics used the FASTRAK (Polhemus, Colchester, VT), with accuracy of 0.2mm and 0.2°[24].

Electromagnetic tracking is an alternative approach for in vivo finger kinematics. It seeks to eliminate issues with line of sight, improve the wearability of the measurement apparatus, and provide information on skin motion. EM trackers take up a much smaller space on the finger when compared to inertial sensors, have been used in the measurement of trigger finger kinematics[25] previously, and do not suffer from the line of sight restrictions

of optical sensors. A direct comparison was made using a mechanical articulator to assess the accuracy of EM tracking when compared to digital optical tracking. The examiners used the gold standard known ranges of motion to compare both the optical and EM trackers. From their results, they determined that measurements from both systems are clinically comparable [26]. It is important to note, however, that they were using an articulator designed to simulate the elbow, so the magnitude of the acceptable accuracy and precision may be different than those required for the finger. The investigation also mimicked bone fixation and did not consider skin motion.

1.4.2.3   Imaging

Imaging techniques can also be used to measure kinematics. Radiographic techniques such as X-ray, computed tomography (CT), and magnetic resonance imaging (MRI) can be used to examine position of bone and soft tissue in the body[27,28]. Four-dimensional computed tomography (4DCT) can also examine the mechanics of the body through a motion, providing continuous scanning capabilities. This type of motion capture is referred to as osteokinematics[29], but is limited to a small field of view and limited to the types of functional tasks that can be examined. Reported in-plane resolution in a study involving thumb CMC motion was 0.39mm[29].

1.4.2.4   Inertial Tracking

Inertial tracking involves using the motion and orientation of the object to track the motion. Commonly used inertial sensors contain three angular—rate gyroscopes (to measure orientation) and three orthogonal accelerometers (to measure position). These position values are fixed to the body frame, but can be transformed using orientations obtained from the gyroscopes through a rotation matrix[23]. In biomechanics it is assumed that both the accelerometer and the underlying body experience the same accelerations[30]. Accuracy of inertial sensor pose has been reported, with the correct setup, to be 2° during dynamic motion[31].

1.4.2.5   Optical Tracking

Optical sensors are usually considered as two main types: active (emit light) and passive (reflect light). These systems are composed of the sources and the sensors. Sensors for optical tracking transform the sensed intensity and direction of light into voltages, and can map direction in either 1D or 2D, depending on the sensor type[23]. To achieve 3D pose data using optical tracking, there must be 3 targets visible for each segment of interest, and additionally there must not be any obstruction that causes less than 3 targets to be visible to the cameras. Some ways to counteract this limitation have been to use effective and varied camera angles, increase the number of markers in a cluster, or changing the mounting geometry[23].

Many previous studies have relied on optical tracking to measure finger kinematics. These studies involved active or passive reflective markers attached to the surface of the skin to measure the joint kinematics[9,13,32]. Optical tracking requires continuous line of sight with the sensors, which is difficult with the so many rigid bodies moving and moving in complex motion pathways. The number of joints within a relatively small volume also plays a factor and therefore the experimental setup must be highly controlled for the use of optical tracking. Alternatively, a previous study used an instrumented glove to measure functional range of motion[33]. The size of the joints, motion pathways, and skin motion were all limitations presented by the authors. The use of bulky trackers may introduce unintended skin motion, fatigue, and produce awkward motion in the participant. Within a study assessing hand kinematics using inertial sensors, a comparison to an optical system was performed. Active optical markers were placed on top of the inertial sensors. The testing involved first full flexion of the index finger (80° RoM), then circular motions of the index finger while fully extended[30].

1.4.3   Skin Motion Artefact

Measuring *in vivo* kinematics requires skin mounted tracking techniques when using optical, inertial, or EM tracking systems. This however, results in skin motion relative to underlying bone, changing what is being tracked[6,34]. This is known commonly as the skin motion artefact (SMA) or soft tissue artefact (STA), and contributes to error in

skin mounted measurement techniques. The effects of this are most severe when analysis involves movement, functional assessment, and cases where deformations may be large. There have been numerous studies attempting to address skin motion in other joints of the body. Benoit *et al* reported that procedures to compensate for skin motion are required to accurately capture the motion of the bony segments. There are currently no standards for STA reporting in the fingers, however a system has been proposed with a variety of metrics for standard comparison for any STAs[35]. Metrics such as root mean squared amplitude (RMS) and mean position vector are used[35]. One paper that examined finger STAs used optical tracking, and therefore reported skin motion in terms of the component translations, as well as a net translation[27]. They have reported magnitudes of skin marker translation as high as 10.9 mm. A study by Ryu *et al*. looked at skin motion utilizing MR imaging and skin mounted optical trackers[27]. The hand postures examined involved the neutral position and two cylindrical grasps of different diameters. They reported that while magnitude of skin motion (1-11mm) varied across healthy subjects, the direction was common, and primarily along the long axis of the finger, tending to move distally. One drawback is that they did not report the effect on the total pose of each marker set, but rather only the displacement. They also did not examine dynamic motion, but rather static positions in grip. Another study by Coupier *et al*. proposed a method of *in vivo* finger kinematic evaluation using optical tracking[9]. Movement examined included finger Flex/Ext and Abd/Add motion, and comparison of the skin mounted optical tracker data to CT data was done. This previous paper reported the STAs in 6DoF, with the mean difference in their three translations (x: 1-2mm, y: 1-10mm, z: 1-2mm) and three rotations (x: 2-7°, y: 5-17°, z: 2-9°) expressed in terms of their landmark coordinate system definition[9].

1.5 Hand Osteoarthritis

Osteoarthritis (OA) is a disease of the whole joint which leads to breakdown of joint cartilage and the bone underneath. Though individuals may experience differing symptoms, common characteristics of OA are joint pain, stiffness, reduced RoM, and swelling[36]. This degeneration occurs due to the inability of the joint to maintain and repair the joint cartilage. Hand osteoarthritis (H-OA) is defined as OA affecting the IP and CMC joints of the hand[37]. Within the U.S, 40% of adults will likely develop H-OA in at least one

hand by the age of 85[38]. One study published by Haugen *et al*. looked at H-OA in the general population using hand radiographs. Their results showed that, among elderly individuals, about 40% of the population had radiographic H-OA, and over 90% of those with H-OA at baseline had progression of the disease in a nine year follow up examination[39]. The incidence of radiographic H-OA was found to be around 34% in this same population[39]. Another study examined the prevalence of H-OA and used imaging to determine diagnosis. Dahaghin *et al*. found that around 60% of the population (greater than 55 years of age) had radiographic H-OA in at least one joint[28].

Diagnosis of H-OA is typically based on symptoms reported by patients and through confirmation using X-ray imaging. Imaging can show loss of cartilage, formation of bone spurs, and other changes commonly associated with H-OA.

Physical activity of the hand is important to maintaining the structural and functional capabilities of the hand. Without enough physical activity, joints weaken, become less mobile, and function decreases. As described earlier in section 1.2, pain and immobility due to the response to joint degeneration may impair and discourage the use of the hands. This lack of activity may contribute to the decrease in hand function and weakness of the affected joints[37]. Additionally, the joint may suffer from increased laxity, due to ligaments around the joint being stretched or damaged due to inflammation or degeneration.

1.5.1　Treatment

Conservative Management

One popular non-invasive method of treating H-OA is the use of a tool or device to aid in daily function. Assistive devices include any component, grip, tool, or mechanism used or designed to help an individual perform a certain task. When applied to H-OA, the most common devices are those used to improve the ability of an individual to perform ADLs, allowing them to continue to function independently (built up handles for tools, altered grips of handles). These devices work by helping to keep the joints better aligned, as well as decrease the force or grip strength required to perform a task[40]. A study by Roda-

Sales *et al.* looked at the effect that various assistive devices had on ADLs. A camera system was used to collect data, and the arm and hand postures were classified qualitatively, with total time in each grasp/posture and total time completing each task being quantified. They showed a reduction in pinch grasps and an increase in palm contact through use of assistive devices[41].

Another non-invasive method, commonly combined with assistive devices, is behavioral change. This can be accomplished by using a joint protection program (JPP)[42]. Often formatted as a pamphlet, booklet, or handout, these programs center around maintaining function, promoting independence, and preventing further damage through proper alignment of the joints. These programs typically have background knowledge on the disease, overarching principles (avoid positions that foster deformity, avoid tight gripping, avoid positions that put pressure on joints, avoid positions that put constant pressure on the joints, and a variety of behavioral changes), and lifestyle modifications (Figure 8) to help improve quality of life and maintain function[42]. Although these methods are thought to be effective, there has been no quantitative examination of joint deformity during functional tasks, and whether adherence to the advice given in JPPs is effective. The recommendations mentioned earlier are therefore not evidence based, and they represent the current best assumptions regarding the use and protection of the damaged finger joints. Another non-surgical method of H-OA treatment is injection of some type of substance to attempt to reduce pain and/or improve mobility. These intra-articular therapies commonly use either corticosteroids or hyaluronic acid[43]. Currently, JPPs are implemented as a non-invasive form of OA treatment, but they have some notable deficiencies. The recommendations can be severely outdated, such as recommendations on the use of rotary phones[42].

Examination of joint protection programs, activities of daily living, and functional tasks has been limited. Vergara *et al.* examined grasp types used during ADLs and reported usage and grasp type. They have reported that in an eight hour day, the pinch grasp is the most commonly used grasp, with it being highly utilized in activities involving food preparation and leisure activities[44]. It is important to note that no quantification of joint kinematics was done in this study. Another study by Amaral *et al.* looked at the

effectiveness of assistive devices against the standard information pamphlet about JPPs. This study measured performance primarily based on the Canadian Occupational Performance Measure and the Score for the Assessment and Quantification of Chronic Rheumatoid Affections of the Hands. They found that assistive devices were more effective for treatment than the information about joint protection[40]. A study by Gracia-Ibáñez *et al* examined the functional RoM of individuals performing a variety of ADLs by using an instrumented glove. They reported absolute and functional range of motion, with an observation that in many cases the absolute RoM of the joints exceeds the functional RoM by more than $10°$[33]. The use of a glove could have resulted in performance of tasks differently, as well as loss of accuracy due to the glove surface sliding with respect to the underlying skin.
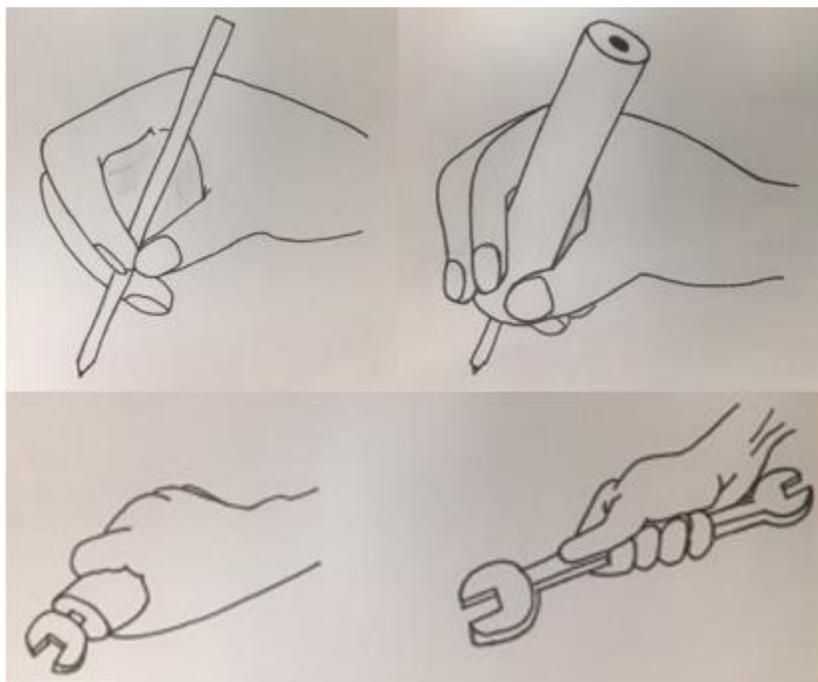
Figure 8: Examples of joint protection program recommendations and tools to avoiding positions that foster deformity
Example joint protection recommendations: When writing, the recommended modification is to use built up handles to help avoid the closed position and soften grip. When using tools, the same recommendation is made, with the added modification of avoiding pressing with the thumb along the handle of the tool.

Surgical Management

Hand Osteoarthritis can be treated, towards the end stage of this disease, using surgical management techniques. Finger joints may be replaced by implants or spacers, or the joint may be fused, which would eliminate movement altogether[45]. The finger joint replacements have been made with pyrocarbon[45], degradable biomaterials[46], and silicone[47]. The pyrocarbon implants were found to have issues with implant migration and limited effectiveness, resulting in Reissner *et al.* (2014) no longer using the implants. The biomaterial implants were found to have complications in many study patients and had a high repeat surgery percentage[46]. Silicone implants have been the most studied and have been found to be very sensitive to ulnar deviation, which caused more wear and plastic deformation of the implant in a study conducted by Drayton *et al*. (2016). There has been research into a surgical procedure involving specifically the thumb CMC joint, which is one of the most common locations for handOA[48]. This procedure involved denervation of the joint, and was shown to help decrease pain and improve function of the thumb[48].

1.6 Rationale

Current methods of evaluation of *in vivo* finger kinematics involve using a manual goniometer (clinical settings) or using optical tracking. A goniometer cannot be used during functional tasks[49], optical tracking has line of sight constraints[9,13,50], and inertial tracking is bulky and may restrict motion considerably[30,50]. Electromagnetic tracking seeks to eliminate these issues by providing non-obstructive, real time measurement that has no line of sight restriction. Application to functional tasks is of high importance, and EM tracking shows potential to be a successful option.

Previous authors have looked at quantification of skin motion artefact, reporting displacements with respect to the underlying bone[9,27]. Limitations of this research was that it only captured skin motion during basic motions of the fingers and was limited to the marker type tested (optical marker clusters). No research was found regarding EM tracking and skin motion, which is important in determining the feasibility of the technique for use. There is a gap in knowledge regarding skin motion of EM trackers during finger motion.

There is currently little quantitative analysis of the kinematic differences (or lack thereof) between normal motion and following a conservative management strategy (JPP techniques). This knowledge would be useful in helping to determine the efficacy of JPPs, improving different task recommendations, and examining new tools or techniques that are to be implemented. This may also help to address the issue of compliance to these JPPs, as patient compliance is low, and quantitative backing may help improve it.

Development of a novel method of describing *in vivo* finger kinematics that focuses on application to activities of daily living (ADLs) and patient specific definition can lead to a better understanding of kinematics of patients with H-OA. These advances can then be used various clinical applications including examining the effectiveness of various joint protection programs in patients with hand arthritis, but also in the examination of finger kinematics in other fields (athletics, office environments, and so on). This research can also have application to design of ergonomic devices and equipment.

1.7 Objectives and Hypotheses

This research seeks to employ the use of electromagnetic tracking to examine finger kinematics (6 degrees of freedom) during functional tasks involving the hand in an *in vivo* biomechanical application. The objectives of this research are:

1. Proposal of an *in vivo* finger kinematic coordinate system, which employs landmark digitization to measure 6 DoF finger kinematics (Chapter 2).

2. Quantify soft tissue artefact and the effect it has on the proposed method (Chapter 2).

3. Validate the proposed method of *in vivo* tracking using a cadaveric model, with bone markers as the gold standard (Chapter 2).

4. Compare *in vivo* RoM reported by the proposed method to a clinically relevant reporting method (goniometer) (Chapter 2 & 3).

5. Examine finger range of motion in a sample of healthy individuals during a selection of activities of daily living (focused on the pinch and precision grasps)

using the proposed method to examine typical RoM values required to perform various functional tasks (Chapter 3).

6. To examine the how these RoM values change when H-OA is present and to quantify how deficiencies in joint RoM translates into functional tasks involving the fingers (Chapter 3).

7. To examine RoM changes when instructing individuals to perform tasks using current JPP principles, and whether the RoM associated with deformity (Abd/Add) changes (Chapter 3).

8. To examine differences in active RoM reported between healthy participants and participants with H-OA (Chapter 3)

Hypotheses

The hypotheses are closely tied to the objectives of this work. The threshold values in the hypotheses are given based on considering literature and guidance from an occupational therapist.

1. Skin motion will be comparable to literature values (no greater than 15mm total displacement) (objective 2)

2. The proposed method will be comparable to the gold standard used in this research, with less than $10°$ difference between the RoM reported (objective 3)

3. The proposed method will be comparable to goniometer measurement (within $5°$ for reported RoM) (objective 4)

4. Participants with H-OA will have decreased Flex/Ext RoM when compared to healthy participants when performing tasks (at least $10°$ in at least one joint) (objective 6)

5. Participants with H-OA will have decreased Abd/Add RoM when compared to healthy participants when performing tasks (at least 10° in at least one joint) (objective 6)

6. Use of JPPs will decrease the Flex/Ext and Abd/Add requirements in both healthy and H-OA affected hands (at least 10° in at least one joint) (objective 7)

7. Participants with H-OA will have reduced active RoM of the finger joints when compared to healthy individuals (at least 10° in at least one joint) (objective 8)

1.8 Thesis Overview

Chapter 2 describes the development of a novel *in vivo* landmark coordinate system approach to measuring finger kinematics. Results from a single participant baseline RoM examination and a single specimen cadaver test (to also measure skin-motion artifact) and are shown to investigate the capabilities of the EM tracking method for kinematic evaluation. This measurement method is evaluated against a manual goniometer, and in the cadaveric specimen also evaluated again bone fixed EM trackers.

Chapter 3 investigates the RoM and joint laxity of a small group of participants (n=10 healthy, n=9 with H-OA) performing ADLs. This chapter examines the effect of health status, task, and method of execution (normal or with JPP principles) on the finger joint motions. The methodology for measuring finger RoM from chapter 2 is applied here, and manual goniometer measurements are compared to EM tracker measurement for simple flexion/extension of the long fingers and thumb. Values are reported for total RoM of the thumb IP, thumb MCP, index DIP, index PIP, middle DIP, and middle PIP during a RoM baseline evaluation (flexion/extension motion), 9 ADLs, and 7 JPP variations corresponding to the ADLs selected.

Chapter 4 provides conclusions, strengths and limitations, and future directions of this research.

Chapter 2

2 Development of a Novel Landmark Coordinate System Definition for Measurement of *In Vivo* Finger Kinematics

In this chapter, a novel method for measuring *in vivo* finger kinematics is proposed. This involved the description of the sensors, fixation method, and landmarks used. Testing was conducted using a healthy participant (n=1), and a cadaveric specimen (n=1). Comparison between the novel method, goniometry and current literature values was done. Cadaveric testing was used to examine skin motion artefact contribution to reported RoM changes and to validate the EM tracking.

2.1 Introduction

Quantifying *in vivo* finger kinematics is a critical component in determining and assessing function of the hand[13]. When considering joint laxity, examining finger kinematics could provide insight into progression and severity of damage to the joint structures. It is also beneficial for improving kinematic modelling of the hand by providing more information of *in vivo* finger segment motion pathways[7].

To measure finger kinematics, the International Society of Biomechanics had proposed standards for kinematic reporting and landmark palpation. They have since updated their recommendations (in 2005)[8,51]. It has since been reported that these landmarks are not practical for *in vivo* applications, as they are not easily accessed[5,9,27,51]. Many papers have reported their methods for landmark palpation or marker location, with no standard protocol being adhered to across research groups[4,5,9,51].

The purpose of this study was to propose an *in vivo* landmark digitization protocol (objective 1) for use with EM trackers in kinematic evaluation, to quantify the soft tissue artefact for EM tracking of finger kinematics (objective 2), to validate the proposed method with a gold standard method of quantifying finger motion (objective 3), and to compare to a clinically relevant measurement tool (objective 4). Measurement of finger segment Flex/Ext and Abd/Add motion are variables of interest for *in vivo* testing. Reported RoM

differences between measurement methods are of interest in *in vitro* testing for examining the impact of skin motion.

2.2 Electromagnetic Tracking System

Data acquisition during all testing methods was conducted employing a 3D Guidance trakSTAR sensor system (Ascension Technologies Corporation, Trakstar, Northern Digital, Waterloo, ON, Canada). This tracking system utilizes a transmitter to create an EM field, within which the sensors operate. The sensors utilize orthogonal inductors, allowing for the pose of each sensor within the magnetic field to be tracked with 6 DoF.

The sensors used were model 180 2mm OD EM sensors purchased from the sensor system manufacturer. The manufacturer specified static accuracy of the sensor system was reported as less than ±1.4mm RMS, and ±0.5° RMS. The sampling rate of 120hz was chosen based on previous studies that investigated finger kinematics, which had sampling rate of 60-120hz[7,34,50,52].

The data format retrieved from the TrakSTAR was chosen to be matrix format, having a position vector and a 3x3 rotation matrix. Sample code from the manufacturer was edited to allow for smooth data acquisition, as the demonstration application they provided did not have the correct formatting. The code allowed for sampling at a specified frequency for a specified duration of time, and the option to exit or collect more samples after each sampling period.

2.3 Finger Mount Development

2.3.1 Mount Profile and Features

Mount design was conducted in solidworks, and mounts were printed using a 3D printer (Figure 9). During the design phase, requirements and specifications were collected and used as a guide for the design process. Mounts were designed so they did not constrain mobility, had curvature that provided good skin contact, and had a hole for the sensor to be secured in using a press fit tolerance with the possibility of a liquid medical adhesive to be added. The skin mounting method utilized a medical adhesive in tandem with medical

tape to ensure a secure fit while maintaining the subject's mobility as much as possible. Athletic tape was used to loosely secure sensor wires to the wrist in *in vivo* applications, as this helped to reduce sensor shifting due to tension on the sensor wires.
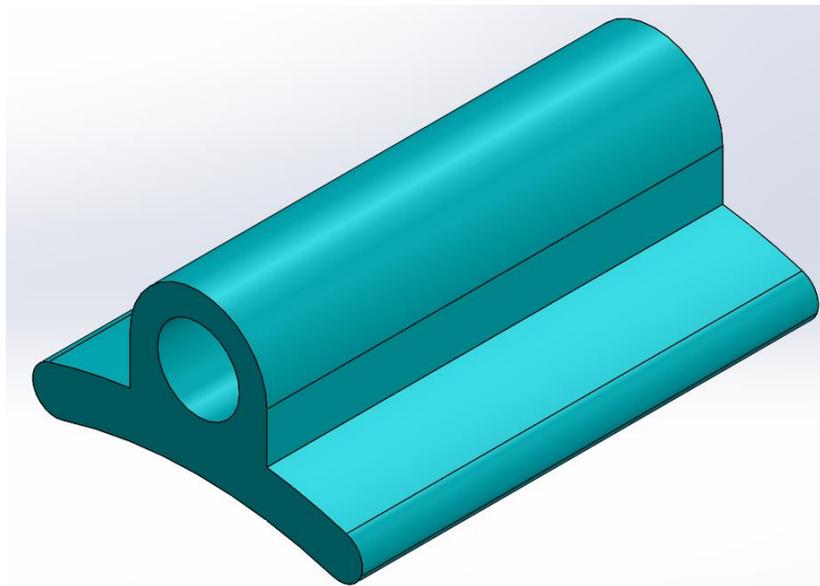
Figure 9: 3D printed finger mount - press fit design

2.3.2   Mount Fixation Method

The mount-skin interface was very important to consider. The mount/sensor assembly needed to be attached to the surface of the skin securely, to eliminate additional movement caused by slippage of the mount over the skin. To do this, a variety of methods were attempted. Medical tape wrapped around the finger and mount was attempted, and it was found that the adhesion was not enough nor consistent. Due to this, a medical grade adhesive (Mastisol) was investigated to supplement the adhesion provided through the medical tape. The adhesive was applied to the underside of the sensor mount and to the dorsal surface of the finger segment (Figure 10) before being attached with medical tape. This combination provided good adhesion to the skin, and was the method used throughout the remainder of this work to fix the sensor mounts to the skin surface.
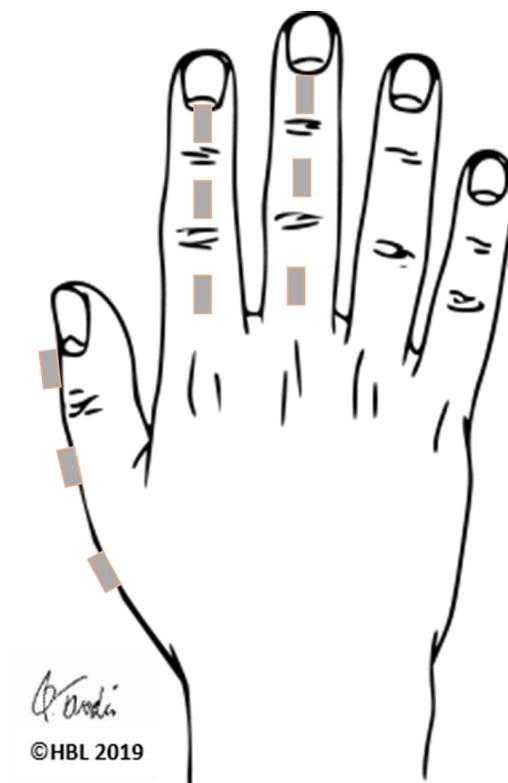
Figure 10: Sensor placement *in vivo*
Sensors (in mount) were placed on the dorsal side of the hand, in approximately the center of the middle and proximal phalanges. The sensor was placed proximal to the nail in the distal phalanges.

2.4   Coordinate System Definition

2.4.1   Coordinate System Selection

As discussed in Chapter 1, there are three main types of coordinate system definition commonly used in biomechanical applications (functional, landmark, and reference). For this application, the following requirements were considered:

- The definition must be as accurate as possible

- It must capture motion in an anatomically relevant way

- The ability to examine laxity should be possible

- Easy to apply *in vivo*

- Cannot be invasive

- Must be applicable in cases of deformity of the joints

Accuracy of the system was an important consideration in this work, as the fingers are very small, and measurement of the motions may prove challenging due to their size. Additionally, it is important for making clinically relevant measurements, as being able to confidently quantify changes through time is important for rehabilitation and treatment purposes. It was important to capture motion in an anatomically relevant way, as without the anatomical reference, the range of motion values and components (Flex/Ext, Abd/Add, Int/Ext) would not be distinguished easily. In joint degenerative disease, as mentioned in Chapter 1, the joints and bony segments may undergo some degree of deformity as the condition progresses. Being able to examine this through the coordinate system definition was of interest. Joint laxity (Abd/Add motion) measurement is important for application to functional tasks. Being applicable *in vivo* while also being non-invasive were major considerations during design. The definition would not be practical if these two criteria were not met.

Through analysis of previous methods and consideration of the requirements discussed above, a landmark coordinate system definition was selected[5]. Using this definition required the selection of landmarks on the finger segments in order to create the anatomically relevant frames for each bony segment, and in turn report the joint RoM measurements.

2.4.2   Anatomical Landmark Definition

Selection of the appropriate landmarks is essential for an effective coordinate system definition. The requirements defined to help aid in selection were:

- Easily accessible *in vivo*

- Easily identifiable

- Easily palpable

- Cannot cause pain or involve any invasive procedures

- Follows guidelines in the literature wherever reasonable

- Allows for simple creation of coordinate frames

To define the landmark coordinate system, information was taken from a variety of papers in the literature[8,51], most notably one that compared functional, landmark, and reference coordinate system definitions[5]. The landmarks found in the literature were adapted to reference features noticeable *in vivo* without the need for an invasive procedure or imaging. Since the landmarks described are all on the surface of the skin, they were easily accessed and palpated using the EM sensor used as a digitizer. Table 1 describes each landmark for each bony segment of interest in this work. Figure 11 gives a visual schematic of the approximate location of each landmark.

Table 1: Landmark location descriptions

Thumb	Distal Phalanx	1. Center of the tip of the finger
		2. Medial bony flare, on the distal side of the IP joint
		3. Lateral bony flare, on the distal side of the IP joint
	Proximal Phalanx	4. Medial bony flare, on the proximal side of the IP joint
		5. Lateral bony flare, on the proximal side of the IP joint
		6. Medial bony flare, on the distal side of the MCP joint
		7. Lateral bony flare, on the distal side of the MCP joint
	Metacarpal	8. Medial bony flare, on the proximal side of the MCP joint
		9. Lateral bony flare, on the proximal side of the MCP joint
		10. Medial bony flare, on the distal side of the basal CMC joint
		11. Lateral bony flare, on the distal side of the basal CMC joint
Index Finger	Distal Phalanx	12. Center of the tip of the finger
		13. Most medial point of the DIP joint, toward the distal end
		14. Most lateral point of the DIP joint, toward the distal end
	Middle Phalanx	15. Most medial point of the DIP joint, toward the proximal end
		16. Most lateral point of the DIP joint, toward the proximal end
		17. Most medial point of the PIP joint, toward the distal end
		18. Most lateral point of the PIP joint, toward the distal end
	Proximal Phalanx	19. Most medial point of the PIP joint, toward the proximal end

		20. Most lateral point of the PIP joint, toward the proximal end
		21. Most medial point of the MCP joint, toward the distal end (try to palpate the bony bump)
		22. Most lateral point of the MCP joint, toward the distal end (try to palpate the bony bump)
Middle Finger	Distal Phalanx	23. Center of the tip of the finger
		24. Most medial point of the DIP joint, toward the distal end
		25. Most lateral point of the DIP joint, toward the distal end
	Middle Phalanx	26. Most medial point of the DIP joint, toward the proximal end
		27. Most lateral point of the DIP joint, toward the proximal end
		28. Most medial point of the PIP joint, toward the distal end
		29. Most lateral point of the PIP joint, toward the distal end
	Proximal Phalanx	30. Most medial point of the PIP joint, toward the proximal end
		31. Most lateral point of the PIP joint, toward the proximal end
		32. Most medial point of the MCP joint, toward the distal end (try to palpate the bony bump)
		33. Most lateral point of the MCP joint, toward the distal end (try to palpate the bony bump)
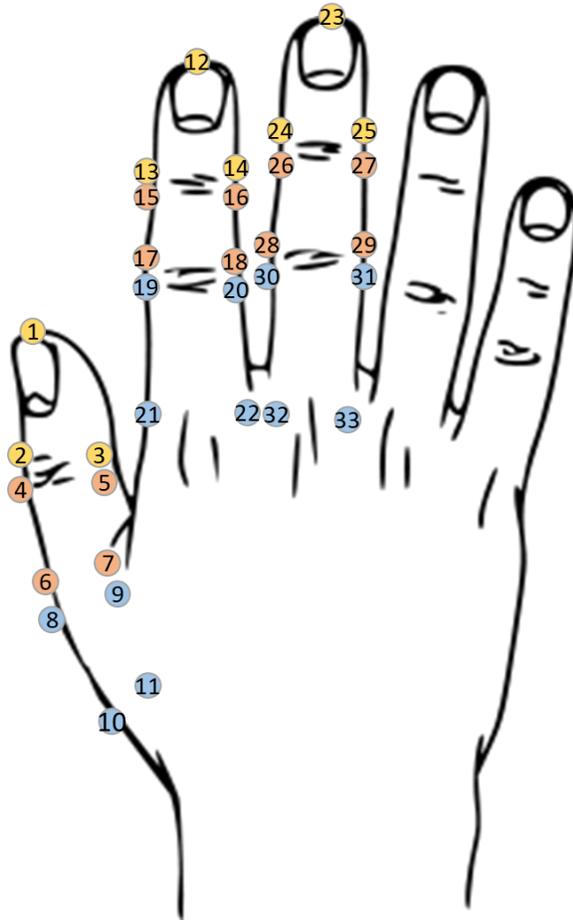
Figure 11: Anatomical landmark locations
Description of all anatomical landmarks developed: The distal landmarks consist of 3 per digit (yellow), and the middle and proximal landmarks consist of 4 per segment (orange and blue, respectively)

2.4.3   Creation of Anatomical Frames from Anatomical Landmarks

Each anatomical frame was defined in comparison to the corresponding tracker attached to the segment (i.e. the proximal index segment frame was defined in relation to the proximal index tracker, resulting in a transformation matrix from the sensor to the landmark frame. This frame was defined using the digitizations as nodes to create vectors between the digitizations (Figure 12). The long axis vector was defined as the vector between the midpoints of the proximal and distal pairs of digitizations respectively. In finger segments with three landmarks, the long axis was defined as the vector from the midpoint of the proximal or distal digitizations to the single digitization (at the finger tip for distal phalanges).

Create Vectors as shown between digitizations and midpoints.

Cross the long axis vector with the proximal medial-lateral vector.

Cross the newly made anterior/posterior vector with the long axis vector.

The resulting landmark frame is created.
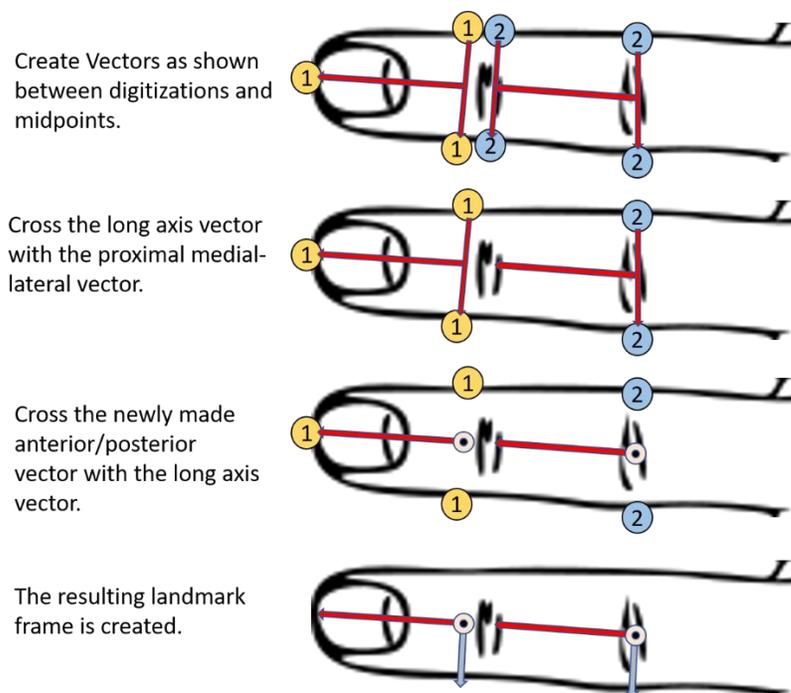
Figure 12: Landmark frame creation

2.4.4   Calculation of Joint Motion

To report the angular motion of the joints, a comparison between the frames axis was considered. This was achieved by regarding the more proximal segment as "fixed" and tracking the motion of the vector between frames with respect to the proximal segments frame definition. The transformation matrix between the two segments was created through Equation 1, with each transformation matrix denoted as described in Table 2. It was important to translate the origin to the joint in question, represented by the midpoint of the vector between the proximal segment's distal digitization points. Care was taken to ensure all manipulations were done within the same frame of reference. All frames and descriptions were done using Euler angle notation, with the rotation order corresponding to the Flex/Ext, Int/Ext, and Abd/Add rotations in order. The middle rotation was chosen to be the Int/Ext rotation as it is highly constrained. Through this method, the angular changes in the vector between the frames in each plane of the proximal coordinate system was considered as representing the Flex/Ext, Abd/Add, and Int/Ext rotations. Equation 1 shows the simplified transformations done to describe the rotation of the distal segment of the joint with respect to the proximal segment, within the proximal segment frame

definition. As all measurement and descriptions were done in cartesian coordinate space, the required matrix manipulations and transformations were done between sensor, transmitter, and segment coordinate system descriptions to achieve the joint motion description (Figure 13). Computation was done using MATLAB.

$$ {}_{D}^{P}T_P = {}_{PS}^{P}T_P * {}_{T}^{PS}T_P * {}_{DS}^{T}T_P * {}_{D}^{DS}T_P \qquad (1) $$

Table 2: Transformation matrix descriptions

${}_{D}^{P}T_P$	Transformation matrix from the proximal segment frame to the distal segment frame, in the proximal segment coordinate description.
${}_{PS}^{P}T_P$	Transformation matrix from the proximal segment frame to the proximal sensor frame.
${}_{T}^{PS}T_P$	Transformation matrix from the proximal sensor frame to the transmitter frame.
${}_{DS}^{T}T_P$	Transformation matrix from the transmitter frame to the distal sensor frame.
${}_{D}^{DS}T_P$	Transformation matrix from the distal sensor frame to the distal segment frame.
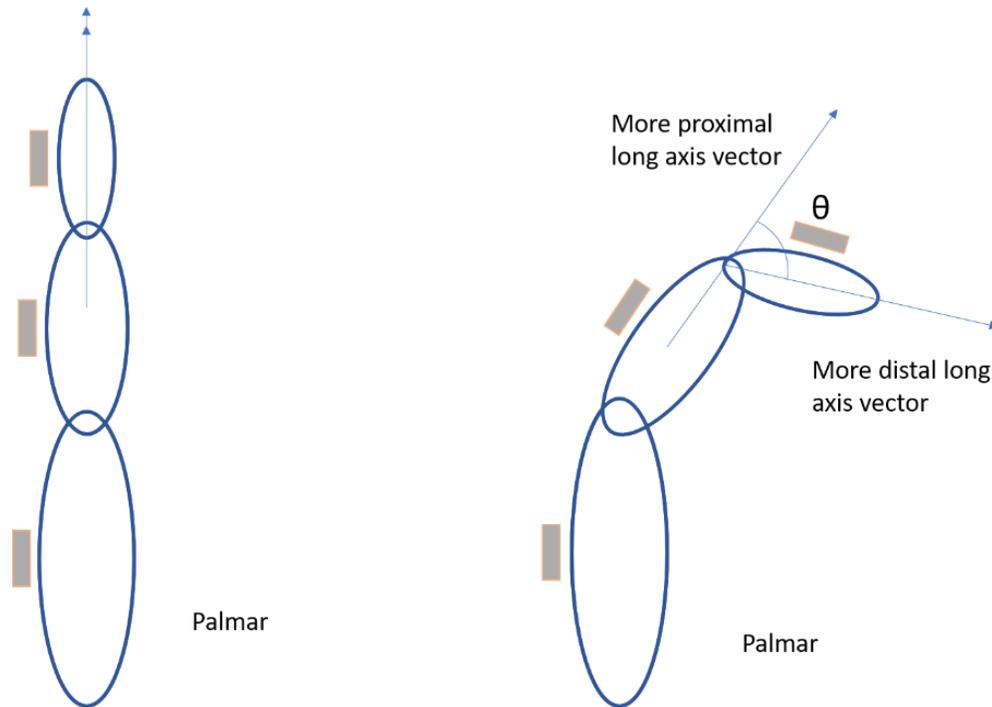
Figure 13: Visual representation of the flexion/extension range of motion calculation

2.4.5   Data Processing

The reported metrics were chosen to be in the form of an anatomically relevant kinematic comparison (joint RoM). In all data processing (Figure 14), a 6th order low-pass Butterworth filter with a cutoff frequency of 5 Hz was used to filter out background noise. A Butterworth filter was selected as it known to have a pass band that is very flat, and higher order filters better approximate the ideal 0 gain past the desired cutoff. The cutoff frequency was chosen based on similarity with literature for kinematic sensing in similar applications[6,10,25,33,53–56].
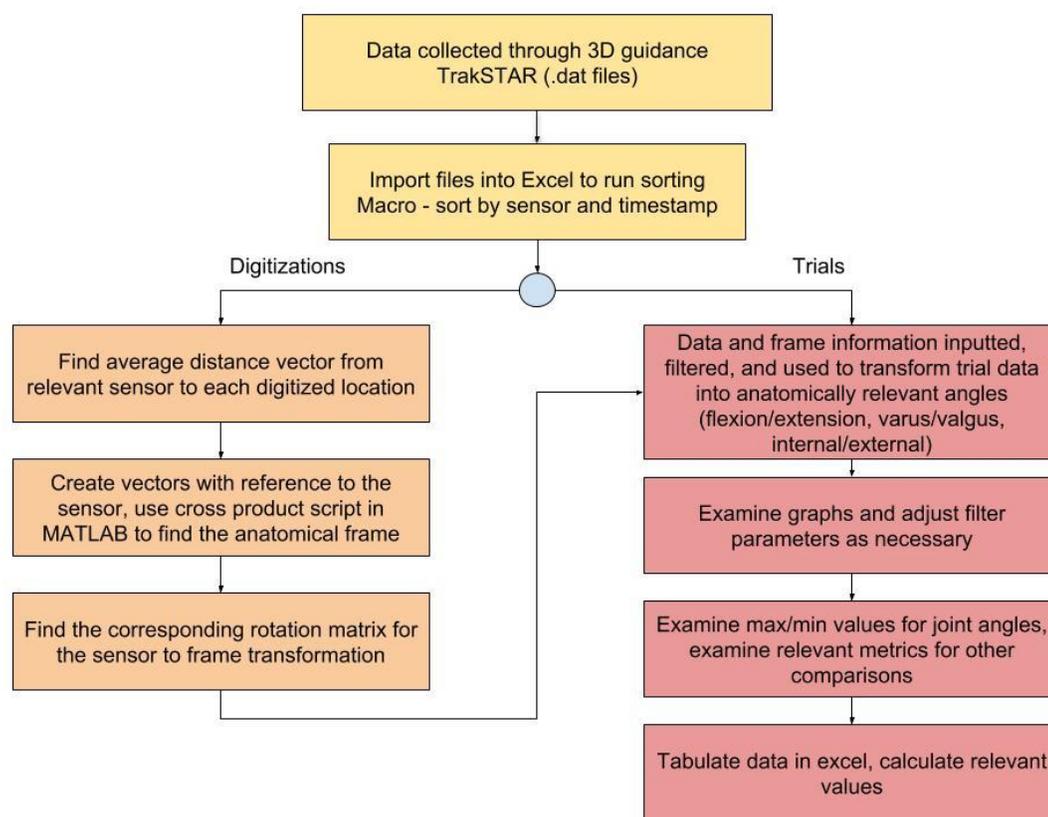
Figure 14: Data processing flowchart

Digitization and trial data were automatically sorted by sensor. To create the coordinate frames, each digitization was paired with the appropriate skin mounted sensor. The coordinates of each digitization with respect to the skin mounted sensor were used to create a long axis vector, proximal medial-lateral vector, and distal medial-lateral vector for each segment. The long axis and proximal medial-lateral vector were then crossed to get the anterior/posterior axis for the segment. This was then crossed with the long axis vector to get the final frame medial-lateral vector as shown previously. These steps created a coordinate frame for each finger segment, allowing for comparison between segments, resulting in the ability to calculate anatomically relevant RoM for each joint based on the segment kinematics.

2.4.6   In Vivo Test Protocol

A right-handed participant (27, F) with no history of trauma or injuries to the hand participated in the study after signing consent. Nine 6 DoF EM trackers (Trakstar, Northern Digital, Waterloo, ON, Canada) were press fit into custom finger mounts, then attached to the dorsal side of the thumb, index, and middle finger segments of the dominant hand using medical adhesive and medical tape. The sensor wires were secured to the wrist using athletic tape, with enough slack that the participant could move freely. Landmark digitization was then done using another EM tracker as the stylus. The tip of the digitization sensor was held in place on each landmark for five seconds. The participant was instructed to rest their hand and forearm in a comfortable position before digitization took place. The participant's hand remained stationary during each digitization but could be moved between digitizations. The hand was positioned with the forearm in a neutral position during digitization of the thumb landmarks for ease of access. The hand was positioned with the forearm in full pronation. After digitization, the participant was asked to perform two main motions, Flex/Ext of the long fingers and Flex/Ext of the thumb. These tasks were chosen as they have been previously used in finger motion evaluation[9]. Each task was done three times, with EM tracker data collected simultaneously with the Flex/Ext measurements from a manual goniometer. The goniometer was used by a trained operator, and this operator was the same across all measurements.

2.4.7   Cadaveric Validation Study

Finger Motion Simulator

In order to examine skin motion effects, a previously developed finger motion simulator[57] was used to simulate Flex/Ext motions using the cadaveric specimen's tendons. Calibration of the flexion and extension endpoints were determined with the aid of a surgical fellow and set as the position parameters within the simulator. Since all tendons were attached to the same motors, full flexion or extension was not guaranteed for all finger joints, as damage to the cadaveric specimen due to excessive force was to be avoided. The simulator operated separate from the sensor system and data acquisition computer.

Data Acquisition

The TrakSTAR system was used in this experiment. The system consisted of four data acquisition boxes synced to one medium range electromagnetic transmitter. A total of 15 sensors were utilized simultaneously, with 7 "paired" based on the segment they were attached to, and the final sensor was used for landmark digitization.

Noise

Noise is created in the data through interference due to metals, especially ferrous metals. To mitigate this during the experiments, the area around the transmitter and sensors was kept as free from metal as possible. The only components that were metal were screws used for cadaver fixation, and the electronics and motors used to manipulate the cadaver hand. The EM tracking system reported noise along with the t-matrix output, allowing for continuous monitoring of the amount of noise present. The numbers associated with the amount of noise were reported in a unique scale created by the manufacturer. After consulting with the manufacturer of the data acquisition system, it was determined that noise at the level of 20 in their noise scale was significant noise. One solution that was found through trial and error was reduction of sampling frequency of the system, as the default was set to be 240hz, much higher than required. A sampling frequency was chosen to be 120hz, which is still high considering the motion being examined, but had the benefit of reducing the noise to 9-12 at the highest, which was viewed as acceptable by the manufacturer.

Experimental Protocol

One fresh frozen cadaver (Female, age 62) was thawed for 22 hours before the test. Radiograph images were examined by the surgical fellow to confirm there was no visible joint damage in the hand. On the testing day, the surgical fellow isolated the flexor and extensor tendons of the index, middle, and ring finger. These tendons were then sutured and attached to the finger motion simulator using 0-Vicryl. No soft tissue or muscle was removed from the cadaver during the entire test procedure. The specimen was then mounted and secured to the simulator using screws to hold the radius and ulna in place,

while the dorsal part of the hand rested on a foam block (Figure 15). Holes were then drilled to accommodate the bone mounted trackers, with the middle finger holes being tilted 45 degrees from the medial-lateral plane to prevent interference with the motion of the other fingers. The trackers were then press-fit into the drilled holes. The skin mounted trackers were press-fit into the finger mounts, and then attached to the dorsal side of the hand using tape and medical adhesive. A full cycle of motion was defined as beginning with the simulator in extension, simulating flexion to the surgeon specified endpoint, then simulating extension to the beginning position. In this study, the gold standard was bone-fixed EM trackers, and this was used to compare results from the skin-fixed EM trackers. Joint RoM reported by the bone and skin mounted trackers was compared for each joint for Flex/Ext, Abd/Add, and Int/Ext rotational directions.
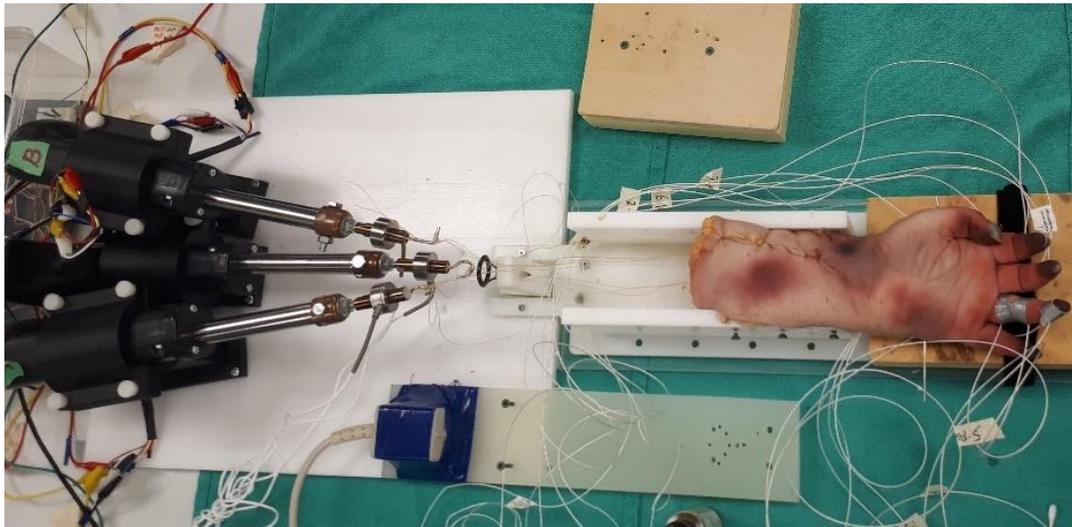
Figure 15: *In vitro* **finger motion simulator setup**
The simulator used was previously developed by Mohammad Haddara under the supervision of Dr. Louis Ferreira. The simulator allows for the simulation of long finger flexion/extension[57]*.*

2.5 Data Analysis

Data were tested for normality of distribution using the Shapiro-Wilk test (SPSS v25, SPSS Inc, Chicago, IL) for the *in vivo,* and *in vitro* test data. The skin mounted tracker Abd/Add data did not satisfy the requirements for normality in the *in vitro* cadaveric test.

In Vivo Participant Test

EM tracker and goniometer reported RoM were examined for homogeneity of variance using Levene's Test (SPSS v25, SPSS Inc, Chicago, IL). Bland-Altmann plots were generated for difference between the EM tracker and goniometer reported RoM in Flex/Ext, Abd/Add, and Int/Ext respectively. A paired t-test was conducted to examine the difference between sampling techniques. Linear regression was done for each pair to look at correlation.

Soft Tissue Artefact

To examine the effect of skin motion on relative sensor motion, proposed guidelines by Cereatti *et al.* were followed. These guidelines use a metric called the RMS amplitude that is used in this work as well[35]. The metrics reported were the cartesian RMS amplitudes (x, y, and z axis) and the total displacement amplitude.

In Vitro Cadaver Validation

Bone mounted EM and skin mounted EM tracker reported RoM were examined for homogeneity of variance using Levene's Test (SPSS v25, SPSS Inc, Chicago, IL). The Abd/Add RoM data did not satisfy this test. Paired t-tests (95% CI) were conducted on the range of motion data (Flex/Ext and Int/Ext) from all trials, with pairs being between the skin mounted and bone mounted RoM values for each rotation direction. A Related Samples Wilcoxon Signed Ranks Test was performed for the Abd/Add RoM comparison of skin mounted and bone mounted trackers. Linear regression was done for each pair to look at correlation, and Bland Altmann plots were constructed for each RoM direction (Flex/Ext, Abd/Add, and Int/Ext rotation). The Bland Altmann plots were used to identify if there were any trends in the variability of the data, and to give a general indication of the spread of the data as they show the difference between the measurement methods plotted against the average value reported.

2.6   Results

In Vivo Finger Motion

Table 3 shows the Mean and standard deviation (SD) of total active range of motion (RoM) reported for each finger segment (thumb, index and middle) for flexion/extension, varus/valgus, and internal/external rotation motions for a single participant (3 trials per motion). Comparison of participant Flex/Ext, Abd/Add, and Int/Ext RoM to literature values[9] is shown in Figure 16,Figure 17, andFigure 18 respectively.

Table 3: Active RoM for a healthy participant in full flexion-full extension motion

Participant Flexion/Extension Range of Motion (Degrees)						
Trial	Thumb IP	Thumb MCP	Index DIP	Index PIP	Middle DIP	Middle PIP
1	73	63	68	89	80	81
2	65	69	64	97	74	89
3	63	72	76	98	83	78
Avg	67	68	69	95	79	83
StdDev	5	5	6	5	5	6
Participant Varus/Valgus Range of Motion (Degrees)						
Trial	Thumb IP	Thumb MCP	Index DIP	Index PIP	Middle DIP	Middle PIP
1	5	19	14	13	8	30
2	5	20	13	17	17	28
3	10	17	15	22	12	30
Avg	7	19	14	17	12	29
StdDev	3	2	1	5	5	1
Participant Internal/External Range of Motion (Degrees)						
Trial	Thumb IP	Thumb MCP	Index DIP	Index PIP	Middle DIP	Middle PIP
1	18	13	16	13	8	24
2	16	9	19	14	9	26
3	12	12	16	18	20	24
Avg	15	11	17	15	12	25
StdDev	3	2	2	3	7	1
All results are in degrees						
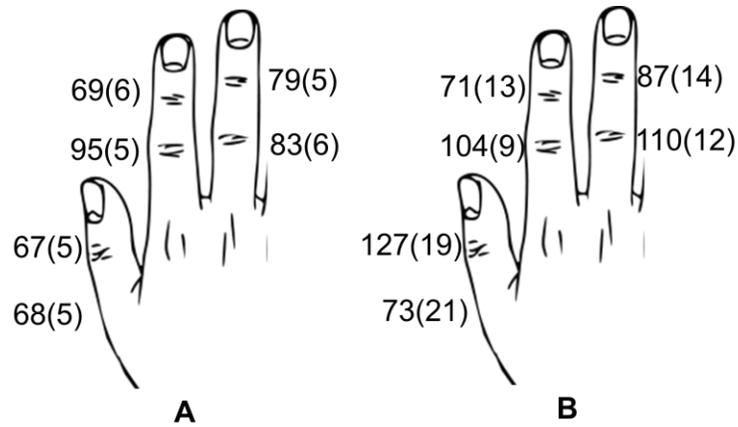
Figure 16: *In Vivo* **Finger RoM measured for Flex/Ext motion**
(Mean and (SD)) measured in (A) this study (n=1, 3 trials) compared to (B) literature values (n=20)[9].
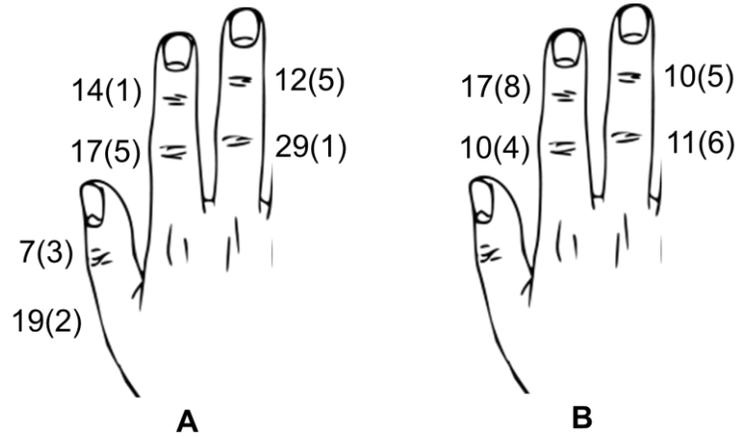
Figure 17: *In Vivo* **Finger RoM measured for Abd/Add motion**
(Mean and (SD)) measured in (A) this study (n=1, 3 trials) compared to (B) literature values (n=20)[9].
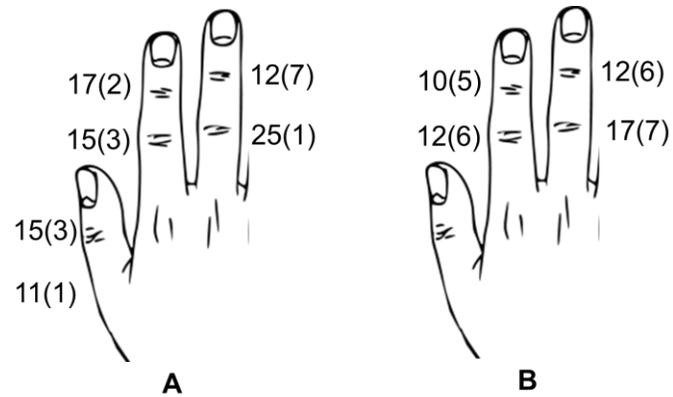
Figure 18: *In Vivo* **Finger RoM measured for Int/Ext rotation**
(Mean and (SD)) measured in (A) this study (n=1, 3 trials) compared to (B) literature values (n=20)[9].

Table 4 shows the total RoM and mean absolute difference (SD) reported by the EM tracking system compared to the goniometer for the thumb, index, and middle fingers of the dominant hand during finger Flex/Ext. Within the current study, mean absolute differences (SD) reported in the thumb were 7°(2) (IP) and 6°(4) (MCP); index finger differences were 6°(6) (DIP) and 7°(4) (PIP); middle finger differences were 5°(4) (DIP) and 4°(3) (PIP). This is also visually displayed in Figure 19 for the Flex/Ext RoM.

Table 4: Comparison of EM and goniometer measurement of joint RoM in a healthy participant (n=1, 3 trials)

Goniometer Comparison of Participant Flexion/Extension Range of Motion (Degrees)						
	Thumb IP			Thumb MCP		
Trial	Goniometer	Sensor	Difference	Goniometer	Sensor	Difference
1	65	73	8	65	63	2
2	60	65	5	60	69	9
3	70	63	7	65	72	7
Avg	65	67	7	63	68	6
StdDev	5	5	2	3	5	4
	Index DIP			Index PIP		
Trial	Goniometer	Sensor	Difference	Goniometer	Sensor	Difference
1	80	68	12	100	89	11
2	70	64	6	100	97	3
3	75	76	1	105	98	7
Avg	75	69	6	102	95	7
StdDev	5	6	6	3	5	4
	Middle DIP			Middle PIP		
Trial	Goniometer	Sensor	Difference	Goniometer	Sensor	Difference
1	75	80	5	85	81	4
2	75	74	1	90	89	1
3	75	83	8	85	78	7
Avg	75	79	5	87	83	4
StdDev	0	5	4	3	6	3
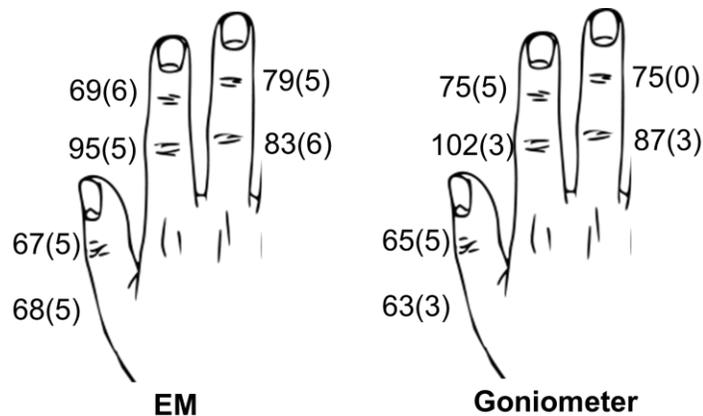
Figure 19: Comparison of measured EM and goniometer Flex/Ext RoM for a healthy participant (n=1, 3 trials)

No significant differences were found between the EM and goniometer reported RoM values (p=0.735, 95% CI [-2.3, 3.2]). Correlation between the measurements was good ($R^2 = 0.78$).

Soft Tissue Artefact

Table 5 shows the Mean relative motion of the skin mounted sensors compared to the bone mounted sensors. Total translation ranged from 4-11mm. It is important to note that the bone mounted sensor in the middle phalanx of the middle finger broke during testing, so no data could be retrieved from it.

Table 5: Relative motion of skin mounted EM sensors compared to paired bone mounted EM sensors

	RMS Difference Between Skin and Bone Fixed EM Sensors							
	Distal Index	Middle Index	Proximal Index	Distal Middle	Proximal Middle	Distal Ring	Middle Ring	Proximal Ring
total translation (mm)	6	7	7	5	4	8	11	8
x (mm)	4	6	2	2	2	6	5	5
y (mm)	4	4	5	4	2	5	4	7
z (mm)	3	3	2	4	5	4	9	2

In Vitro Validation

Figure 20,Figure 21, and Figure 22 show absolute differences in Flex/Ext reported in the index finger were 4°(3) (DIP) and 5°(4) (PIP); ring finger differences were 6°(4) (DIP) and 7°(4) (PIP).Absolute differences in Abd/Add reported in the index finger were 6°(5) (DIP) and 5°(3) (PIP); ring finger differences were 5°(4) (DIP) and 8°(12) (PIP), Absolute differences in Int/Ext reported in the index finger were 5°(3) (DIP) and 5°(3) (PIP); ring finger differences were 5°(4) (DIP) and 5°(4) (PIP).
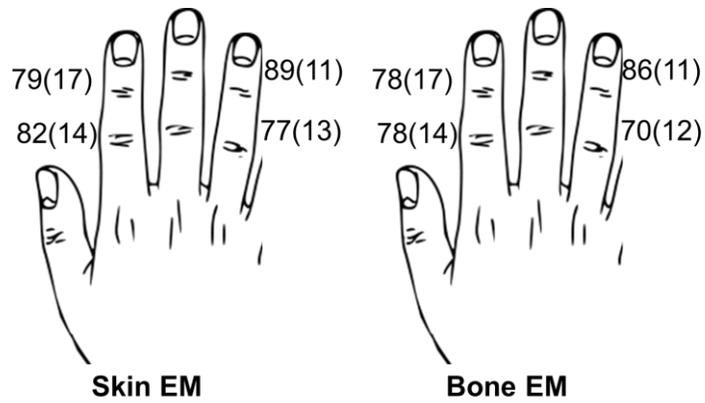
Figure 20: Comparison of bone and skin mounted EM tracker reported Flex/Ext RoM (n=1, 16-19 trials)
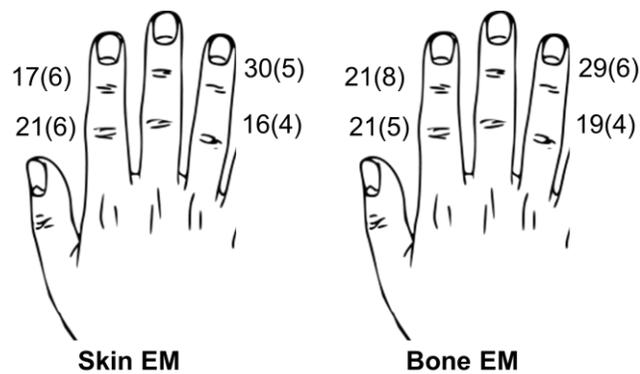
Figure 21: Comparison of bone and skin mounted EM tracker reported Abd/Add RoM (n=1, 16-19 trials)
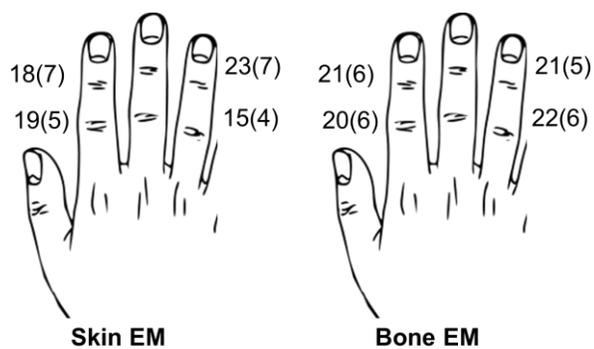
Figure 22: Comparison of bone and skin mounted EM tracker reported Int/Ext RoM (n=1, 16-19 trials)

Significant differences were found in the Flex/Ext (p=0.000, 95% CI [-5.4, 2.7]) and Int/Ext (p=0.000, 95% CI [1.7, 4.5]). No significant difference was found in the Abd/Add RoM comparison (p=0.490, 95% CI [-0.7, 2.2]). Linear correlation between measurements was good in Flex/Ext ($R^2 = 0.82$) and Adb/Add ($R^2 = 0.29$), and low in Int/Ext ($R^2 = 0.15$).

Bland-Altmann plots of the reported skin and bone mounted RoM are presented in Figure 23-Figure 25. There is no clear pattern of the spread of the data increasing or decreasing as joint RoM changes. The mean difference between the bone and skin mounted measurement methods was -4.0° (Flex/Ext), 0.8° (Abd/Add), and 3.1° (Int/Ext).
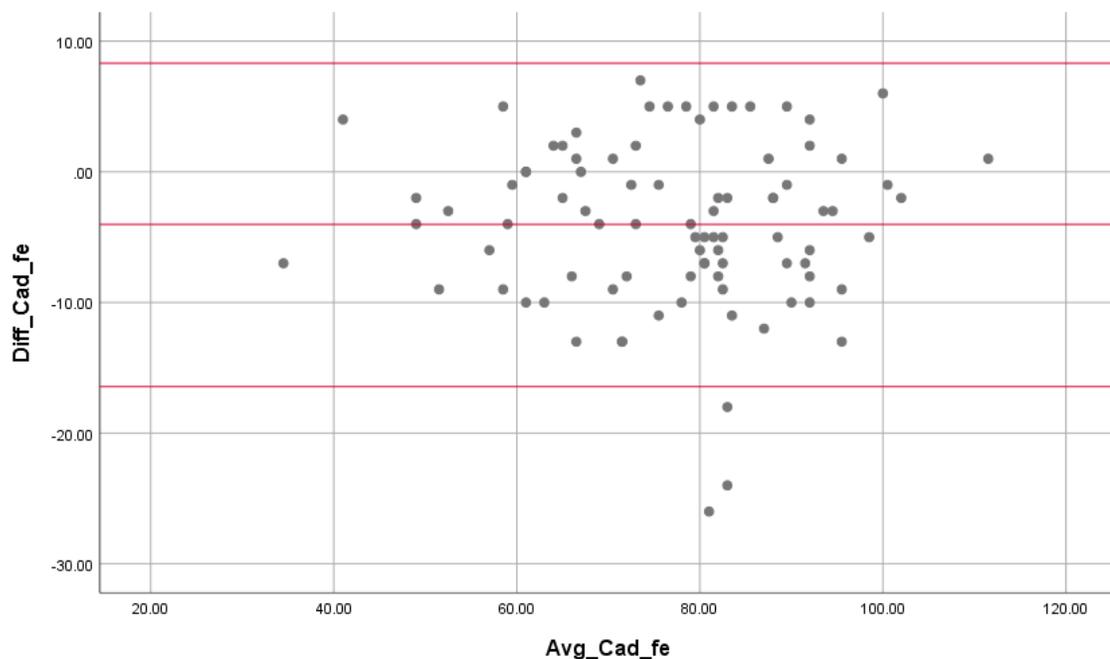
Figure 23: Bland-Altmann plot of the difference between bone EM tracking and skin EM tracking for the Flex/Ext RoM
N=1 hand, 89 measured comparisons across the index, middle, and ring fingers.
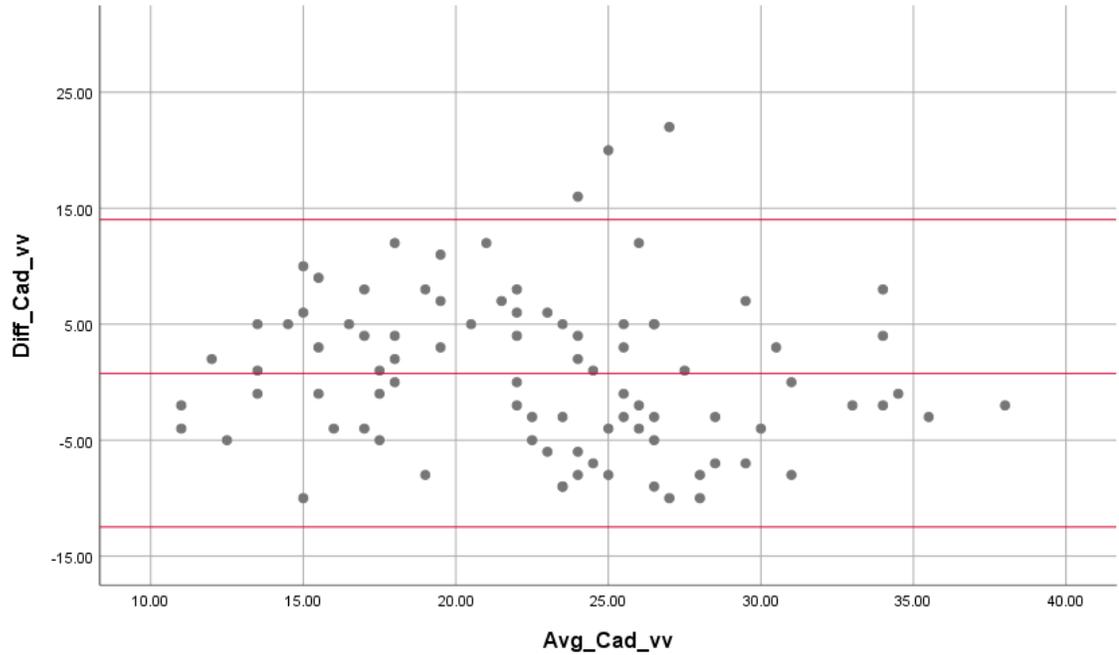
Figure 24: Bland-Altmann plot of the difference between bone EM tracking and skin EM tracking for the Abd/Add RoM

N=1 hand, 89 measured comparisons across the index, middle, and ring fingers.
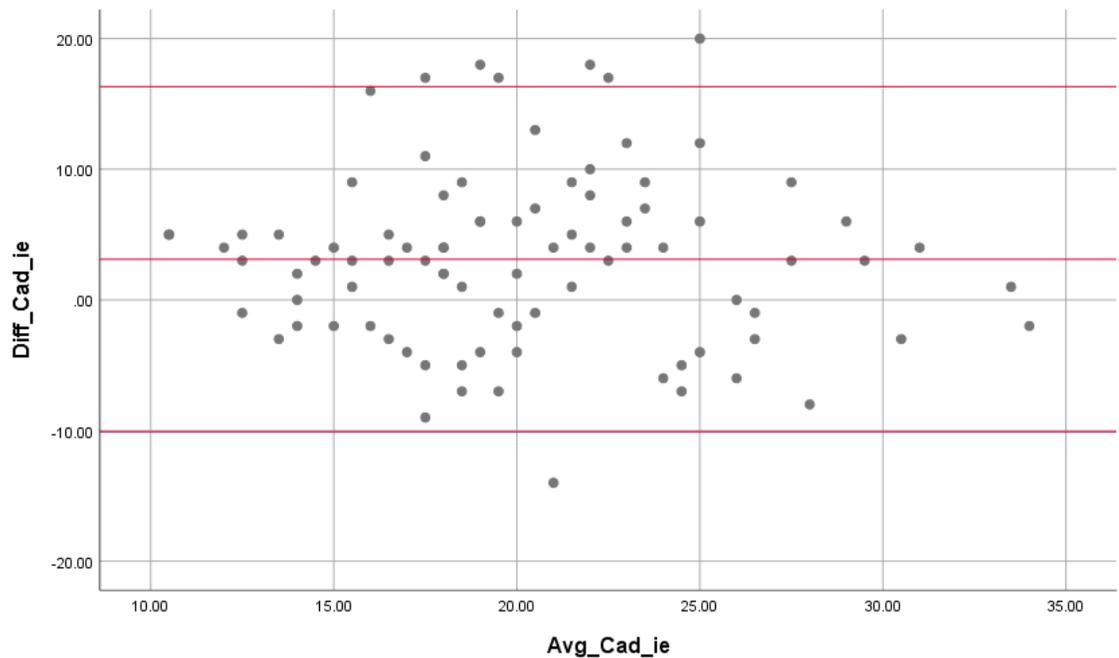
Figure 25: Bland-Altmann plot of the difference between bone EM tracking and skin EM tracking for the Int/Ext RoM

n=1 hand, 89 measured comparisons across the index, middle, and ring fingers.

2.7   Discussion

The purpose of this study was to develop an *in vivo* landmark digitization protocol that employs EM trackers to measure finger kinematics (objective 1) and to then quantify skin motion artefact (objective 2) and validate measured finger kinematics using a gold standard (objective 3). Range of motion of six finger joints (including the thumb, index, and middle fingers) were presented from data collected on a single participant performing total Flex/Ext. Results are comparable to values measured using a manual goniometer for Flex/Ext total RoM across all joints to within 5°(3) (objective 4), and absolute RoM values fall within ranges previously reported in the literature[9,11,33]. The *in vitro* cadaver validation (comparing bone marker to skin marker) led to similar Flex/Ext, Abd/Add, and Int/Ext RoM values (mean differences lower than 7°) during the Flex/Ext motion. In the Bland Altmann plots, at least 95% of the data fell within the upper and lower limits, indicating a good result. Skin marker translation was found to be 4-11mm RMS. Through the results presented, the proposed method of *in vivo* finger kinematic tracking is equivalent to manual goniometer measurement and allows for the measurement of Abd/Add as well. Skin motion did not have a clinically significant effect on joint RoM (differences in cadaveric specimen reported joint RoM were less than 5°).

The finger RoMs reported in this study were compared to those reported in similar studies for Flex/Ext, Abd/Add, and Int/Ext. It was found that the Flex/Ext (67-95°), Abd/Add (5-30°), and Int/Ext (8-26°) values reported in *in vivo* testing paper were comparable to those reported in other studies[5,9,10]. The values presented in this study agree with values presented in the literature review, however there are still areas where error could be introduced. The coordinate frames created for each finger segment will not always be perfectly aligned with the axis of rotation or the underlying bone, which could have introduced small errors in all rotation directions. Noise was present in the signal throughout testing and could have introduced error into the measurement as well.

Soft tissue artefact in finger Flex/Ext motion was examined in this paper, and reported as RMS difference to follow proposed standards in the literature[35]. Ryu *et al*. used magnetic resonance imaging and optical tracking to examine skin movement of the metacarpal during Flex/Ext motion and found total motion up to 10.88mm[27]. This was

comparable to the current paper, with skin movement reported below 12mm. An important distinction to make is that the relative motion values give an indication of the magnitude of skin motion, but do not necessarily indicate how much the reported RoM differs, as seen in the *in vitro* validation. Since RoM values are close, and skin motion magnitude agrees with the literature, skin motion does not affect the reported RoM by more than 5° on average.

In vitro validation resulted in an examination of the difference in the finger joint RoM reported by each method. A study by Metcalf *et al.* examined using markerless motion capture for measurement of hand kinematics in home-based applications. They examined the grasping motion for holding a cup, and found that their methods reported joint angles with 10-12° maximum error when compared to their gold standard[15]. Chang *et al.* compared surface markers, geometric modelling, and fluoroscopy and found index finger Flex/Ext RoM differences up to 9.7° between fluoroscopy and surface markers and up to 7.34° between the geometric model and fluoroscopy[58]. This was comparable to this current paper, with differences up to 7° in Flex/Ext RoM. The *in vitro* results in this paper showed that skin motion does not severely impact the measured flexion/extension range of motion through skin and bone fixed sensor comparison (mean difference less than 5° overall). The Abd/Add and Int/Ext measurements made during the flexion/extension motion were not severely impacted as well (mean differences less than 5° overall). It is important to note that the difference in reported values could be attributed to several limitations. Some error may be attributed to sensor accuracy and the higher amounts of noise seen in the *in vitro* testing, but other factors, such as skin or bone (or both) trackers slipping or moving unintentionally could attribute to the larger discrepancies. The cadaver skin was much harder to apply tape to, even after wiping it down to try to increase adhesion of the medical tape. This led to the use of a different, more adhesive tape that would not be applied *in vivo*. This may have changed the kinematics of the experiment; however, it was the best option to achieve the same effect as the *in vivo* application.

In cases where there was a statistically significant difference between groups being compared, the 95% CI was examined to see if the difference reported was also clinically

significant. In all cases, the 95% CI range for the mean difference was always within 5° of zero. This is an acceptable level of difference between Mean RoM reported.

Previous studies measuring finger kinematics have also compared their results to other tracking methods. In this study, finger flexion and extension were measured using the EM sensors as well as using a hand-held goniometer. Coupier *et al*. compared their results with goniometer measurements and reported a mean difference of Flex/Ext 10°±14 between stereophotogrammetry and goniometer measurements[9]. Similarly, this current study reported a maximum difference in Flex/Ext of 11° for one joint. It is important to note that in both studies, this maximum was much higher than the values for mean difference and may indicate an issue with sensor or marker fixation. Nataraj *et al* (2013) compared a kinematic model to an optical marker set and found differences in the Flex/Ext angle reported as great as 19°±7[13]. Both the *in vitro* and *in vivo* testing within this current study demonstrate smaller differences between skin mounted EM tracking and the comparison measurement for Flex/Ext RoM.

There has been research into the quality of goniometer measurement as a gold standard. McVeigh *et al* (2016) examined trained professionals in the field and found that goniometer measurements were not consistently measuring to ±5° of the measurements on radiographs[49]. The consistency of goniometer measurement may have influenced the statistical significance of comparisons that were not quite statistically similar. The in vitro validation conducted within this paper did a comparison that used bone mounted EM trackers as the comparison measurement. This increases the robustness of this study, showing that the measured angles of skin mounted trackers are comparable to those of bone mounted trackers for flexion/extension range of motion.

An alternative to landmark coordinate systems is utilizing screw displacement axis methods (also called helical axis). This is referred to as a functional frame and has been described in Chapter 1. Landmark and functional frames were compared in the literature, and they found that there was no significant difference between the two for examining motion[5]. In this paper, landmark frames were selected to allow for patient-specific

definitions. The use of a landmark frame definition in this study is done to help better capture deformity in the finger segments and joints[5].

The methodology of this study allowed for a robust examination of the use of EM tracking for in vivo finger kinematics. Utilizing cadaveric validation, *in vivo* testing, digitization repeatability, goniometer comparison, and literature comparisons helps strengthen the results obtained. The challenge of quantifying skin motion was considered using the cadaveric test and helped to examine the effect in this application. The *in vivo* methods focused on evaluation of the thumb, index, and middle fingers for *in vivo* application, which has relevance to pinch and precision tasks. These grips are utilized heavily in daily activities, with a study finding that the pinch grasp is the most frequently used grasp overall[44].

There are some general limitations in this study. The thumb was not simulated *in vitro*, as the simulator was not designed to simulate thumb motion. The Flex/Ext RoM was the only plane in which goniometer comparisons were done, as Abd/Add and Int/Ext were not done due to limitations of using a manual goniometer. The *in vivo* data is only pilot test data and may not completely capture the results of a larger sample group.

2.8   Chapter Summary

This chapter presented a novel method for digitizing landmarks on the finger *in vivo*, creation of anatomically relevant frames, and measurement of RoM using EM tracking technology. Pilot *in vivo* participant testing, *in vitro* cadaveric validation, and a skin motion artefact analysis was conducted. The measurement technique was determined to be able to measure *in vivo* finger kinematic RoM, and additionally was not severely impacted by skin motion.

To examine the *in vivo* finger kinematics of individuals during different tasks, this landmark definition methodology needs to be applied in a pilot study. A small sample of participants with and without H-OA should be recruited, and a selection of ADLs should be performed. The developed protocol offers the opportunity to examine the differences between healthy and arthritic joint RoM in real time, during ADLs.

Chapter 3

3 Examination of *In Vivo* Finger Kinematics in Healthy and Arthritic Hands During Activities of Daily Living

In this chapter, examination of healthy participants and participants with arthritis performing ADLs was performed. This involved utilizing the *in vivo* experimental protocol from Chapter 2 to examine the finger kinematics of healthy participants (n=10) and participants with arthritis (n=9) performing nine ADLs, with and without JPP principles applied. Joint RoM was compared between each group during each task. Additionally, a comparison within each group (healthy and H-OA) was done to examine RoM differences in the performance of tasks based on JPP principles. A comparison of goniometer and EM tracker reported RoM of the finger joints was also done.

3.1 Introduction

As stated previously in Chapter 1, there are many barriers to evaluating and quantifying finger kinematics, especially when functional tasks/motions are examined. It is important to examine finger kinematics during functional activities because the hand is the most used part of the body for ADLs[59]. Previous studies have quantified finger kinematics[9,10,13,16,17,60,61], however kinematic analysis of functional tasks is still limited[59]. Studies that have examined functional tasks are limited by sample size[11,19,41,62], variety of tasks examined[19,63], joints examined[62,63], and lack of quantitative joint kinematic data[41,44,64]. Comparisons between healthy participants and participants with a joint degenerative disease were also limited, and only considered in a few studies found[16].

Therefore, the purpose of this study was to use the EM tracking system and novel landmark digitization protocol described in Chapter 2 to examine joint RoM during ADLs involving pinch and precision grip tasks (objective 5), to examine healthy and arthritic RoM requirements for these tasks (objective 6), to compare RoM and finger laxity between the two groups, and to compare the normal and JPP recommended methods of performing each ADL (objective 7). A comparison of joint RoM between groups was also done for the baseline active RoM measurements as outlined in the *in vivo* testing protocol of Chapter 2

(objective 8). Finally, a comparison of goniometer and EM tracker reported RoM was done (objective 4).

3.2 Experimental Apparatus

3.2.1 Activities and Measured Variables

Activity selection was based on the selection of fingers to sensorize. In this study, the thumb, index, and middle fingers were to be examined, due to their relative importance in significant grasps such as pinching[65], which make up a larger proportion of hand postures used during ADLs[44]. Nine activities of daily living (ADLs) were selected with input from an Occupational Therapist that used precision and pinch grasps and are commonly performed[33,44]. The JPP recommendations were based on previously recommended techniques[42] as well as the principles of JPP (Avoid positions that foster deformity, avoid tight gripping, and avoid positions that put severe pressure on the joints)[42]. Table 6 lists the tasks examined in this study, the associated JPP recommendations, and images of the tasks and assistive devices (where applicable).

Table 6: Description of tasks, JPP recommendations, and assistive devices used

Task	JPP	Task Image	Assistive Device
1. Plug in/unplug an electrical plug	Keep wrist in neutral position, use multiple fingers		
2. Unlock a doorknob with a key	Use assistive device		

3. Squeeze a spray bottle	Use multiple fingers		
4. Open a water bottle	Use assistive device		
5. Do up a snap	Do not do		
6. Turn a lever tap on/off	N/A		
7. Turn a standard tap on/off	Use the palm of the hand to apply pressure, keep wrist in neutral position		

8. Do up a button on a shirt	Use assistive device		
9. Write a sentence	Use assistive device		
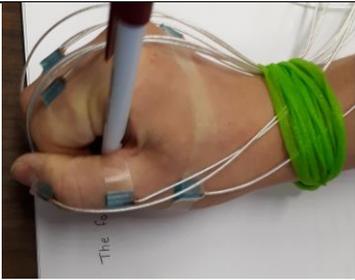
3.3 Experiment

Study Protocol

Ten healthy participants (mean age = 28) and nine participants with arthritis (mean age = 72) that met the inclusion criteria participated in this study after reviewing the letter of information and signing consent. Inclusion Criteria for healthy participants was over 18 years of age with no history of hand disease or injury. Participants with arthritis were chosen such that they were above the age of 18 and had a clinically diagnosed joint degenerative disease (H-OA, or both H-OA and rheumatoid arthritis).

Each participant then filled out a patient demographic form, and a patient rated hand and wrist evaluation (PRWHE) form. Data acquisition was conducted using the EM tracking system (3D Guidance trakSTAR sensor system, Ascension Technologies Corporation) investigated in Chapter 2. The sensor position, fixation method, and landmark

digitization followed the process outlined in Chapter 2. The participant was then asked to perform flexion/extension of the long fingers. Goniometer measurements were taken at full extension and full flexion. This was repeated three times. This procedure was then repeated for the thumb (full flexion, full extension, three repetitions).

Following the digitization and baseline range of motion testing, the participants were guided through the set of nine ADLs chosen for the experiment. In each task, the participant was instructed on what task they would be doing and asked to perform the task with no guidance from the examiner. They were then asked to repeat the task again. As previously described in Chapter 1, joint protection programs are a self-management strategy to help individuals preserve their joints. Joint protection includes alternative movement patterns/strategies perform a task, which typically aim to reduce forces at the joint and avoid positions that foster deformity[42]. The programs also include the use of assistive devices to protect the joints. In this study, individuals were asked to perform the ADL's in their 'normal' way, and then individuals were given instruction on how to incorporate joint protection strategies in their next trial. The second trial for each method (normal and JPP) were included for analysis. Tasks were not randomized in this study.

Range of Motion Calculation

The post processing used to examine the joint RoMs was conducted as described in Chapter 2, repeated for the thumb, index, and middle fingers. Using this method of describing relative rotation across a joint, the Flex/Ext, Abd/Add, and Int/Ext rotations of each joint were calculated during each ADL.

3.4 Data Analysis

The results of this study examine Mean RoM in Flex/Ext and Abd/Add directions for n=10 healthy participants and n=9 participants with arthritis performing a variety of ADLs. It also examines differences between RoM based on health status and method of performance (uninstructed/normal vs JPP instruction). For statistical analysis, all significance values were based on an $\alpha=0.05$ (two-tailed). For all analyses that include tests of normality and variance, the Shapiro-Wilk test for normality was used, and the Levene's

test for equivalence of variance was used. Analysis was conducted using SPSS (SPSS v25, SPSS Inc, Chicago, IL).

To detect differences between healthy and H-OA affected RoM during baseline measurement an independent samples test was run. Since the data did not consist of only normally distributed data sets, the Mann Whitney U test for independent samples was run for each joint in the Flex/Ext and Abd/Add RoM values.

To detect differences between healthy and H-OA affected RoM during ADLs, a few steps were taken. First, all data was examined for normality and equivalence of variance. The data was not normally distributed in all cases, and not all cases satisfied the equivalence of variance test, so a non-parametric Kruskal Wallace test was used in the comparison of healthy and arthritic joint RoM during ADLs (for each joint, during each task).

To detect differences between normally performed ADLs and the same ADLs performed using JPP recommendations, a repeated measures analysis of the healthy and H-OA affected groups (respectively) was done. Since the data was not normally distributed, a non-parametric repeated measures Wilcoxon signed ranks test was done across all joints for each pair of tasks (plug, key, spray, bottle, tap, button, and sentence) for each group based on health status (healthy or H-OA affected).

To detect differences between EM measured RoM and goniometer measured RoM, a paired samples test was conducted. Both groups of data satisfied the normality and equivalence of variance tests, so a paired samples t-test was used.

3.5 Results

The primary objective of this study was to examine differences in RoM between healthy participants and participants with arthritis performing ADLs involving pinch and precision grasps that utilize the thumb, index, and middle finger. The secondary objective was to examine differences in RoM based on how each activity was performed (normal or with JPP recommendations). RoM values for the thumb IP and MCP, index DIP and PIP,

and middle DIP and PIP joints are presented for 10 healthy participants and 9 participants with arthritis performing 9 ADLs.

Demographics

Nineteen (19) participants (10 healthy participants; 9 participants with H-OA) were examined in this study (demographics data is shown in Table 7). Participants with H-OA were clinically diagnosed, with varying degrees of severity and joints affected. The PRWHE score was used to stratify the pain and disability of each participants wrist/hand[66]. In this study, the scores were grouped into 3 categories: a score of 0-20 was classified as low-no pain/disability, a score of 20-80 was classified as moderate pain/disability, and a score over 80 was classified as severe pain/disability. Through this scoring, the degree of hand related disability was quantified[67].

Table 7: Demographics data

	Healthy Participants	Participants with Hand Arthritis
Gender		
Male	7	3
Female	3	6
Age		
18-35	9	0
36-50	0	0
51-65	1	3
65+	0	6
Hand Dominance		
Right	9	9
Left	1	0
Form of Arthritis		
Osteoarthritis	0	8
Osteoarthritis + Rheumatoid Arthritis	0	1
Patient Rated Wrist/Hand Evaluation (PRWHE)		
No Pain (PRWHE < 20)	10	5
Moderate Pain (20 < PRWHE < 80)	0	3
Extreme Pain (PRWHE > 80)	0	0
Missing	0	1
Years Arthritis Diagnosis		
1-10	0	2
10+	0	5
Unsure/missing	0	2

Participant RoM

Mean RoM for healthy participants and participants with arthritis were collected during flexion/extension motion for the long finger and thumb (Table 8).

Table 8: Mean (SD) RoM during finger flexion and extension of healthy participants and participants with arthritis

		Flex/Ext		Abd/Add		Int/Ext	
		H	A	H	A	H	A
Finger Flexion/extension movement (SD)°							
Thumb	IP	77(21)	70(18)	10(6)	13(7)	20(11)	16(6)
	MCP	48(17)	43(18)	16(8)	13(9)	15(5)	14(6)
Index	DIP	71(19)	42(10)*	10(3)	16(5)*	19(5)	15(10)
	PIP	96(10)	78(17)*	18(6)	16(7)	20(10)	15(8)
Middle	DIP	82(18)	55(19)*	15(9)	13(4)	27(10)	21(9)
	PIP	102(11)	80(30)	21(10)	20(12)	35(25)	28(6)

* Denotes significant differences when compared to healthy RoM ($\alpha=0.05$)
H - Healthy participants   A - Participants with H-OA

Participant RoM During ADLs

The RoM for each participant during each task was recorded. Mean RoM was reported for all joints, for all tasks (both performed normally and with JPP recommendations), within each status group (healthy and H-OA). A graphical representation can be found in Appendix H. Significant differences between healthy and H-OA RoM, healthy normal and JPP recommended task RoM, and H-OA normal and JPP recommended task RoM are visually presented. Differences between compared RoM values of 10° or more are also noted (Table 9, Table 10, Table 11)

Table 9: Mean (SD)° RoM of participants during activities of daily living in Flex/Ext and Abd/Add directions for the Thumb (IP and MCP) finger segments.

Red text indicates a difference of greater than 10° from the comparable healthy or normal RoM. Symbols represent the associated significant difference as indicated in the table legend.

	Thumb IP								Thumb MCP							
	Healthy				Arthritis				Healthy				Arthritis			
	Flex/Ext		Abd/Add		Flex/Ext		Abd/Add		Flex/Ext		Abd/Add		Flex/Ext		Abd/Add	
Task	Normal	JPP	Normal	JPP	Normal	JPP	Normal	JPP	Normal	JPP	Normal	JPP	Normal	JPP	Normal	JPP
Plug	43 (25)	38 (23)	11 (8)	9 (4)	40 (17)	61 (26)	11 (4)	11 (3)	39 (15)	31 (13)	12 (4)	11 (5)	37 (12)	45 (16)	14 (5)	13 (7)
Key	73 (17)	51 (21) †	25 (8)	14 (5)	59 (22)	47 (17) †	24 (9)	16 (7) ‡	45 (18)	34 (11) †	15 (6)	12 (4)	53 (21)	41 (17)	18 (7)	14 (5)
Spray	49 (30)	51 (29)	8 (2)	7 (2)	35 (12)	29 (12) †	8 (4)	10 (3)	35 (14)	32 (19)	13 (3)	13 (4)	32 (14)	33 (6)	10 (4)	15 (7)
Bottle	40 (18)	47 (23)	12 (5)	10 (7)	33 (15)	35 (22)	9 (3)	11 (4)	39 (10)	37 (17)	14 (4)	19 (7)	44 (15)	43 (18)	18 (6)	15 (6)
Tap	38 (25)	42 (18)	8 (1)	9 (4)	27 (17)	33 (20)	9 (2)	11 (4)	34 (13)	31 (16)	14 (4)	13 (4)	43 (15)	32 (9) ‡	12 (4)	11 (6)
Button	29 (23)	26 (20)	8 (4)	8 (3)	27 (18)	25 (15)	9 (7)	6 (2)	37 (18)	25 (13) †	12 (5)	10 (5)	36 (11)	34 (18)	11 (6)	12 (7)
Sentence	41 (25)	40 (22)	6 (2)	8 (3)	41 (25)	45 (30)	7 (4)	7 (5)	29 (21)	31 (14)	12 (5)	11 (5)	32 (11)	31 (12)	11 (7)	10 (6)
Snap	35 (32)		7 (2)		30 (12)		8 (4)		34 (18)		11 (5)		39 (14)		13 (4)	
Levertap	32 (13)		9 (4)		31 (15)		9 (3)		37 (12)		14 (4)		39 (14)		14 (7)	

* = significantly different from healthy RoM
† = significantly different from normal RoM for healthy participants
‡ = significantly different from normal RoM for participants with hand osteoarthritis

Table 10: Mean (SD)° RoM of participants during activities of daily living in Flex/Ext and Abd/Add directions for the Index (DIP and PIP) finger segments.

Red text indicates a difference of greater than 10° from the comparable healthy or normal RoM. Symbols represent the associated significant difference as indicated in the table legend.

	Index DIP								Index PIP							
	Healthy				Arthritis				Healthy				Arthritis			
	Flex/Ext		Abd/Add		Flex/Ext		Abd/Add		Flex/Ext		Abd/Add		Flex/Ext		Abd/Add	
Task	Normal	JPP	Normal	JPP	Normal	JPP	Normal	JPP	Normal	JPP	Normal	JPP	Normal	JPP	Normal	JPP
Plug	81 (18)	69 (15) †	14 (8)	20 (7)	53 (22) *	61 (15)	22 (8)	19 (6)	73 (15)	55 (19) †	18 (7)	15 (7)	59 (21)	64 (30)	18 (11)	20 (6)
Key	71 (17)	74 (5)	26 (7)	23 (9)	65 (14)	51 (8) *‡	31 (11)	28 (6)	89 (10)	59 (20) †	23 (9)	20 (8)	71 (16) *	56 (16)	28 (10)	21 (6)
Spray	63 (21)	60 (20)	9 (2)	9 (3)	38 (15) *	40 (19)	10 (4)	14 (8)	59 (15)	58 (23)	11 (2)	9 (3)	45 (23)	45 (27)	9 (3)	10 (2)
Bottle	71 (17)	67 (15)	12 (6)	13 (5)	45 (19) *	45 (10) *	17 (10)	16 (8)	64 (16)	57 (14)	11 (4)	12 (7)	53 (22)	48 (24)	15 (7)	12 (6)
Tap	62 (14)	49 (29)	9 (4)	8 (3)	30 (18) *	27 (11)	9 (5)	14 (7) ‡	62 (23)	58 (22)	10 (3)	12 (8)	50 (23)	42 (19) ‡	9 (3)	11 (5)
Button	59 (28)	55 (18)	8 (3)	11 (11)	32 (21)	36 (20)	9 (2)	10 (4)	58 (17)	51 (21)	11 (4)	11 (4)	53 (24)	45 (28) ‡	10 (5)	11 (6)
Sentence	55 (22)	51 (22)	6 (2)	7 (2)	35 (21)	23 (13) *‡	14 (9)	14 (10)	56 (27)	48 (23)	10 (6)	9 (6)	48 (31)	44 (24)	10 (5)	10 (5)
Snap	64 (26)		9 (2)		35 (15) *		12 (4)		53 (24)		11 (3)		50 (22)		11 (5)	
Levertap	56 (13)		9 (4)		33 (14) *		11 (8)		58 (19)		11 (5)		50 (21)		11 (4)	

* = significantly different from healthy RoM

† = significantly different from normal RoM for healthy participants

‡ = significantly different from normal RoM for participants with hand osteoarthritis

Table 11: Mean (SD)° RoM of participants during activities of daily living in Flex/Ext and Abd/Add directions for the Middle (DIP and PIP) finger segments.

Red text indicates a difference of greater than 10° from the comparable healthy or normal RoM. Symbols represent the associated significant difference as indicated in the table legend.

	Middle DIP								Middle PIP							
	Healthy				Arthritis				Healthy				Arthritis			
	Flex/Ext		Abd/Add		Flex/Ext		Abd/Add		Flex/Ext		Abd/Add		Flex/Ext		Abd/Add	
Task	Normal	JPP	Normal	JPP	Normal	JPP	Normal	JPP	Normal	JPP	Normal	JPP	Normal	JPP	Normal	JPP
Plug	67 (16)	66 (19)	21 (12)	16 (5)	59 (23)	45 (20) ‡	17 (7)	19 (8)	84 (12)	87 (15)	25 (9)	19 (8) †	60 (25) *	55 (26) *‡	19 (11)	19 (9)
Key	80 (14)	67 (18)	27 (11)	19 (5)	54 (8) *	48 (13) *	31 (10)	18 (3)	79 (24)	73 (16)	29 (8)	21 (5)	66 (19)	53 (21) *‡	29 (9)	20 (9)
Spray	46 (26)	50 (34)	11 (9)	11 (8)	30 (12)	35 (20)	8 (2)	10 (4)	77 (30)	64 (30) †	12 (5)	10 (4)	45 (25) *	47 (30)	11 (4)	13 (5)
Bottle	67 (30)	68 (18)	16 (9)	16 (9)	55 (9)	35 (11) *‡	15 (6)	18 (7)	93 (13)	77 (14) †	14 (6)	17 (8)	50 (22) *	49 (24) *	16 (9)	17 (10)
Tap	61 (20)	58 (32)	14 (5)	12 (8)	45 (14)	31 (16) *	16 (6)	12 (4) ‡	80 (20)	63 (35) †	20 (8)	15 (8)	52 (31)	43 (31)	11 (7)	11 (4)
Button	70 (22)	53 (22)	12 (7)	14 (8)	48 (17) *	43 (14)	12 (5)	15 (8)	79 (27)	66 (24)	22 (9)	17 (8)	46 (28)	43 (29)	14 (9)	11 (6) ‡
Sentence	74 (14)	67 (17)	18 (10)	15 (8) †	47 (11) *	45 (13) *	17 (5)	13 (6)	67 (16)	66 (20)	20 (8)	20 (5)	44 (31)	40 (31) *	13 (7)	13 (8)
Snap	61 (31)		11 (6)		42 (14)		12 (3)		84 (18)		18 (5)		55 (30) *		14 (6)	
Levertap	51 (27)		15 (8)		34 (11)		15 (5)		84 (16)		18 (7)		63 (31)		13 (5)	

* = significantly different from healthy RoM
† = significantly different from normal RoM for healthy participants
‡ = significantly different from normal RoM for participants with hand osteoarthritis

Goniometer Comparison

A comparison of the EM tracker RoM and goniometer RoM was made for the flexion/extension baseline RoM task. A Bland Altmann plot was also constructed to show the spread of the data, with horizontal lines at the mean and two standard deviations to either side (Figure 26).
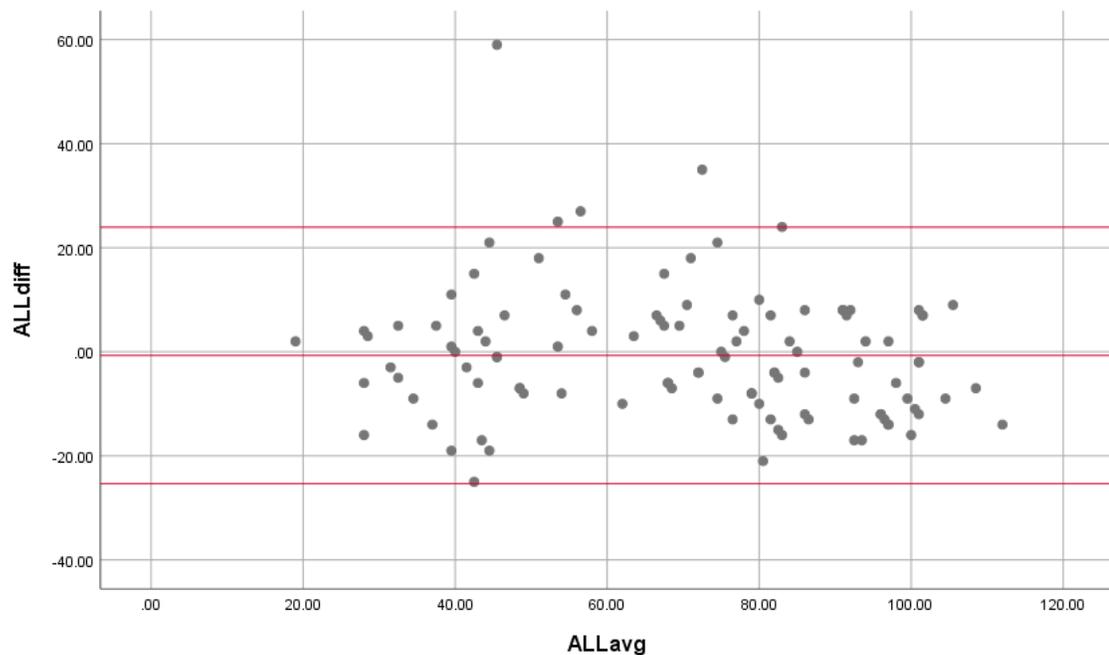

Figure 26: Bland Altmann plot of goniometer and EM tracker reported Flex/Ext range of motion

Mean differences between EM tracker reported RoM and goniometer RoM were also reported (Table 12). No significant difference was found between the measurement methods.

Table 12: Goniometer and EM tracking comparison in the Flex/Ext full RoM task

EM and Goniometer Measured RoM Comparison (°)				
Mean	Std. Deviation	95% Confidence Interval		p (2-tailed)
		Lower	Upper	
-1	13	-3	2	0.556

3.6 Discussion

Joint RoM was quantified during nine ADLs in both healthy participants and participants with arthritis. The results compare well to similar studies in the literature. It is important to note that studies in the literature that have examined these tasks look at healthy participants only in most cases. Bain *et al.* reported the functional F/E RoM for 10 healthy participants performing 20 tasks as 19-71° (MCP), 23-87° (PIP), and 10-64° (DIP), and the active F/E RoM as -19-90° (MCP), -7-101° (PIP), and -6-84° (DIP)[11]. They reported total active RoM and functional RoM for the entire set of tasks performed and did not separate based on task or grasp type[11]. Leitkam *et al* reported significant differences in RoM in the Flex/Ext direction during a series of basic RoM tasks[16]. Stansfield *et al.* examined the upper limb kinematics of healthy participants performing 5 functional tasks at varying points of interest. They reported MCP joint angles of the long fingers, as well as thumb MCP and IP joint angles[62]. due to limitations of line of sight, they did not report the DIP and PIP values for the long fingers. A study by Tamara *et al.* looked at the kinematics of opening a jar. This study measured rotational contribution of each hand during restrained and unrestrained opening of the jar, and found that the restrained procedure changed the contribution of each hand to the task[63].

Significant differences in RoM between healthy participants and participants with H-OA were found for a variety of joints during a variety of the ADLs examined. These results indicate there is a difference in how healthy individuals and individuals with H-OA perform the ADLs specified. These differences indicate that H-OA quantitatively affects the ability of an individual to perform ADLs. This finding agrees with current literature

regarding kinematic differences in the hand between healthy and affected individuals. Leitkam *et al* compared healthy and reduced function hands. Their results indicated that participants with arthritis had decreased RoM compared to healthy individuals in the MCP (5.50°), PIP (6.88°), and DIP (19.42°)[16]. The study was limited in that it did not examine ADLs, but rather looked at different static postures.

When examining whether JPP recommendations affected how healthy participants performed ADLs, significant differences were found. This indicates that JPP recommendations change the way that healthy individuals perform ADLs from a kinematic perspective. When examining whether JPP recommendations affected how participants with H-OA performed ADLs, significant differences were found in specific joints during specific tasks. This indicates that JPP recommendations change the way individuals with H-OA perform ADLs from a kinematic perspective. Some JPP recommendations reduce the required RoM in some joints during the performance of some tasks. Roda-Sales *et al.* quantified hand and arm kinematics based on posture during ADLs, and how assistive device use affected time spent in each posture. They tested assistive devices for tasks such as unscrewing a bottle cap, using a tap, and eating with utensils. They found that assistive devices reduced the frequency of precision grasp use, and increased the use of power grasps[41], as defined by Vergara *et al*[44]. They did not however, present quantitative values for the change in RoM used.

In this study, healthy participants have higher baseline RoM values when compared to participants with H-OA. Within the literature, studies have examined RoM of the fingers. When comparing these results to the healthy RoM reported in this research, it was found that the RoM was similar for the joints examined (PIP and DIP). It is important to note that Bain *et al.* does not report thumb RoM values. Leitkam *et al.* examined nine healthy participants and recorded RoM values for all finger of the hand using optical tracking. They reported total joint F/E RoM for the thumb IP (128.0°), thumb MCP (73.3°), index DIP (92.5°), index PIP (117.6°), middle DIP (99.5°), and middle PIP (126.0°)[17], all of which are higher than those reported within this research or within other joint RoM papers. It is

possible that these differences are due to the small sample size of this work and the definition of full flexion and full extension. A study by Gracia-Ibáñez *et al.* examined RoM of the finger using a glove during a variety of tasks. They reported participant F/E RoM to be 114.5° (thumb IP), 47.1° (thumb MCP), 112.6° (index PIP), and 103.3° (middle PIP)[33]. These values are slightly higher than those reported in this research, which may be due to differing methods of testing full extension and full flexion of the finger joints. The study did not look at Abd/Add RoM for joints other than the MCP joints of each finger. A study by Coupier *et al.* examined RoM of the long fingers in the Flex/Ext and Abd/Add directions. They reported Flex/Ext RoM in 20 healthy participants for the thumb IP (83°), thumb MCP (59°), index DIP (64°), index PIP (100°), middle DIP (81°), and middle PIP (108°) , and Abd/Add RoM for the thumb IP (15°), thumb MCP (10°), index DIP (17°), index PIP (9°), middle DIP (9°), and middle PIP (9°). These values agree well with the results of this chapter, as ADLs were examined, which are expected to increase the Abd/Add motion of the joints.

When comparing between goniometer and EM reported joint angles, the mean difference was less than 5°, and there was no significant difference between the measurement techniques. This result confirms results presented in chapter 2 that state the EM tracker estimated joint RoMs are similar to those provided by a manual goniometer for Flex/Ext. This is a clinically relevant comparison, as goniometers are the most commonly used reference tool for joint RoM evaluation in practice[49].

Within this study, there were many RoM comparisons that were not statistically significant that reported RoM differences of 10° or greater. These values indicate that there is opportunity for future studies to investigate these tasks/joints to examine the differences more closely. When results are reported, statistical as well as clinical significance are important. Currently, goniometer accuracy is clinically accepted as ±5°[68]. When discussing clinically relevant joint RoM change, many more factors are considered in addition to the accuracy of the measuring instrument. The joint total RoM is also considered, as the amount of change that is seen may be compared to the total RoM such that a larger change

may need to be seen in more mobile joints for it to be considered clinically significant. Generally, 10° of change in a finger joint's RoM is considered clinically significant. Another factor examined in clinic is how receptive a joint is to being stretched when heat is applied. This is commonly tested using the modified weeks test. This helps to better inform a clinician's decisions when looking at recovery from an injury but may also have application to degenerative diseases. In almost all tasks, at least one finger joint showed a difference of greater than 10° in Flex/Ext RoM when comparing healthy and H-OA, as well as when comparing between normal and JPP recommended motion techniques. Though these were not always statistically significant differences, they show that this approach has promise as a clinically relevant tool.

An important distinction to mention is total RoM and functional RoM. This research measured total range of motion for each task, as participants returned to a fully extended position after each task was completed. Other literature[11,33] has examined the functional RoM of the fingers, and is a consideration for future research.

This research looked at only the thumb, index, and middle fingers. This was done for a variety of reasons. Each EM tracker has a physical wire that must be connected to the DAQ boxes. When examining the test protocol, it was found that attaching sensors to the 3 digits specified took about 10 minutes, in addition to the time needed to conduct the digitization protocol. Increasing the protocol length was a concern, as the possibility of fatigue was a concern. Additionally, a study examining grasping techniques during a work day found that pinch grasps were the most frequently used grasps[44]. This informed the decision to proceed by examining the thumb, index, and middle fingers in this study, and does not rule out the possibility of examining the other fingers in future work.

When examining demographic data, the mean age for the healthy participants was much lower than that of the participants with H-OA. This was a limitation of the study, as a confounding factor of age was not controlled for. Additionally, study participation requirements were not very strict, resulting in the potential grouping of individuals with varying severities of H-OA, varying ages, and varying functional impairment. This may

have increased the spread of the data and may have caused RoM differences to become less apparent in the small sample set.

Soft tissue artefact and goniometer accuracy were limitations as discussed and characterized in Chapter 2. These areas of variability increase the amount of error present in the experiment. The lack of an imaging gold standard, such as CT, was a limitation. The data was compared to goniometer measurement and literature sources to check agreement; however, CT data would provide a much stronger comparison. This was not done due to constraints as well as the desire to not require imaging for this protocol. Another limitation was that, although the individual administering the test procedure was experienced with the use of a manual goniometer, they were not a clinician. Inaccuracies or increased error may have resulted from this during the goniometer measurements. Noise in the EM tracker signal was also a limitation. Sources of noise were kept to a minimum in all cases, removing any metal in the area when possible. Additionally, a Butterworth low pass filter was used to filter out high frequency background noise to improve evaluation of the RoM.

3.7 Chapter Summary

In this chapter the novel method for measuring finger kinematics *in vivo* was applied to a small group of participants. Nine tasks were completed, each with and without the JPP recommendations available (when possible). The results showed that individuals with H-OA have reduced RoM in some joints and that JPP recommendations change how both healthy participants and participants with H-OA move one or more of their thumb, index, and middle finger joints during certain ADLs (Table 9, Table 10, and Table 11). These results indicate more investigation into the kinematic differences resulting from JPP application is necessary, and additionally whether these principles are beneficial to healthy individuals as well.

4   Conclusion

This chapter provides a summary of the work presented in this thesis. A review of the objectives and hypothesis from Chapter 1 is presented. It then provides a discussion of

the strengths and limitations of the work, followed by a discussion of future directions considered, and finally closes with the significance of this research.

4.1 Summary

Studies have examined finger kinematics and ADLs. Previous studies have been limited by a variety of factors, such as landmark access, task diversity, and sample size. Additionally, JPPs lack quantitative backing, and limited research has been done on the effect of joint disease and JPP application on finger kinematics. The most utilized method of measuring finger kinematics is currently optical tracking systems, which suffer from line of sight restrictions, limiting the applicability to functional tasks at times. The application of EM tracking to *in vivo* finger kinematic tracking during ADLs has not yet been assessed.

Proposed in Chapter 2, the novel landmark coordinate system developed in this thesis was designed specifically for use *in vivo*, with easily palpated landmarks. The digitization protocol was used in conjunction with 6 DoF EM trackers and allowed for anatomically relevant kinematic tracking for Flex/Ext and Abd/Add motions (objective 1). Quantification of STA effects on joint RoM (objective 2) was accomplished through cadaveric specimen testing, reporting a maximum RoM difference of 7°, and a maximum magnitude of skin motion of 11mm. This agreed with the hypothesis that differences due to skin motion would be less than 10°. An *in vivo* pilot study and a cadaveric validation study (objective 3) were conducted to examine the applicability of the proposed coordinate system definition to *in vivo* finger kinematic measurement. This was less than the 10° cutoff hypothesized. Through the *in vivo* testing protocol, it was found that EM reported RoM values were within 5° of manual goniometer reported measurements (objective 4), as hypothesized.

Chapter 3 used the procedure examined in Chapter 2, examining the RoM requirements of healthy participants and participants with arthritis during nine ADLs (objective 5). A comparison based on health status was conducted (objective 6), as well as

a comparison of the method used for task completion (objective 7) (normal or with JPP recommendation). There were significant differences in at least one joint across tasks in the Flex/Ext direction. There were no significant differences in joint RoM in the Abd/Add direction. Range of motion requirements are statistically different in Flex/Ext for some joints in both participant groups based on the method used in each task (normal or with JPP recommendation). Differences were also reported that were greater than 10° in Flex/Ext RoM based on task performance. This indicates that JPP techniques have a measurable effect on the kinematics of the fingers in the Flex/Ext direction. This supports the hypothesis that JPP techniques decrease joint Flex/Ext RoM. Differences reported in Abd/Add RoM based on task performance were not greater than 10°. This does not support the initial hypothesis that JPPs decrease the Abd/Add motion of the joints. It was found that there are significant differences in baseline Flex/Ext RoM between healthy and arthritic joints (objective 8), and additionally that there were cases where the joint RoM difference was greater than 10°. This supported that hypothesis that participants with H-OA would have decreased RoM in baseline Flex/Ext evaluation. Similar to the analysis in Chapter 2, a comparison to goniometer RoM values was made for the baseline measurements (objective 4). These were found to be statistically similar, with a mean difference less than 5°. This further supports the hypothesis that reported RoM values would not differ from goniometer values by more than 5°.

This work has demonstrated that EM tracking is a viable method of measurement for *in vivo* finger kinematics during ADLs. Differences in RoM between healthy participants and participants with H-OA during ADLs were also demonstrated. This research also showed that JPPs have a quantifiable effect on joint RoM for some tasks, and that the joints that are influenced vary depending on the task. Further work must be done to confirm these initial results, and to stratify participant groups with more detail.

4.2 Limitations and Strengths

The studies within this thesis are not without limitation. One such limitation was the comparison measurements used (goniometer measurement and literature results). The

goniometer itself has a degree of uncertainty in its measurements, and these errors may contribute to differences between the goniometer reported joint angle and the EM tracker measured angle. Use of literature results was necessary as the goniometer did not provide a method for measuring the Abd/Add and Int/Ext motions of the joints.

This thesis used a commercial electromagnetic tracking system, resulting in some limitations. The system itself has accuracy specifications for both position and rotation, which add error to measurements made with the system. This error becomes larger when comparisons between different sensors are done, as each sensor's position and orientation are subject to the system error. This may contribute to larger or smaller differences between reported joint RoM and goniometer/literature values and may also affect the RoM values reported during participant testing (ADLs).

Noise from the environment was another limitation of this study. The amount of noise was controlled as best as possible given the experimental apparatus (metal was removed when possible, the sensors and transmitter were as far away from any metal as possible). Finally, the system utilized in this thesis was wired. This was not a limitation for the studies presented in this document however it would be a barrier to applications such as evaluation at home, over a workday, or in applications where travelling across distances is required.

The use of a cadaveric model to examine skin motion and validate the proposed method was another limitation. Cadaveric specimens, even fresh-frozen ones, do not behave exactly as a hand would *in vivo*. Additionally, the insertion of the bone mounted sensors involved cutting of the skin and underlying tissue, which may have influenced the kinematics of skin motion in the *in vitro* testing.

Goniometry was used to measure and compare *in vivo* Flex/Ext values with the proposed method. There was no inter/intra-rater reliability conducted on these values, which provides another potential source of error in the study.

Since a landmark digitization definition was selected, it has some inherent drawbacks. The frame of reference generated, although it has been shown to be consistent, is subject to some error due to misalignment. This may cause rotational error due to the frame not being perfectly aligned with the true bony anatomy position. This was a known limitation when choosing this definition and explained previously in chapter 2. A repeatability analysis was conducted, and the results can be found in Appendix E.

This work was only concerned with the thumb, index, and middle fingers during *in vivo* participant testing. This may exclude useful information about the ring and small fingers. A large amount of wires would have been necessary to sensorize each finger, and this was a consideration when selecting the fingers to examine. The thumb, index, and middle fingers were selected due to their impact during pinch and precision tasks.

Though there are many tasks considered ADLs, there were only nine selected and examined in this study. Due to this limitation, the results presented may not fully capture the differences or similarities in the performance of the ADL based on health status or performance method.

When performing *in vivo* testing, the participants were not instructed on how to perform each task in the "normal" situation. This resulted in individual variability in the method of completing each task, which was not accounted for. Additionally, fatigue and time of day were not explicitly controlled for. The time of day for all testing was between 9am and 2pm, and the test procedure was approximately one hour in duration. This could have let to decreased RoM in tasks performed later in the test procedure.

When conducting statistical analysis for this work, there were cases where non-parametric tests had to be used due to limitations in the data sets. Since this work included development of the method, a small pilot sample of *in vivo* participants was taken. The lack of a large sample size could cause significant differences to appear insignificant and may also cause individual differences to have a much larger influence on the reported results. This also brings up the discussion of power analysis. Power analysis was not completed on

these experiments, as the sample size was low already. Power analysis is crucial in future testing to determine in advance the required sample size, or in post-hoc analysis to ensure the testing had adequate power. These limitations can be avoided in future testing by increasing the sample size for each group to allow for the use of parametric statistical testing and ensuring appropriate statistical power.

Another limitation is the demographics in this study. Overall, the age of participants with arthritis was higher than those who were healthy, which is not accounted for in the analysis. One study by White *et al.* looked at differences in CMC joint RoM based on age and gender, and found a weak correlation for only the CMC abduction motion[69]. Further research may need to be conducted on age related differences in finger RoM to determine whether this must be controlled for in future studies. This may be remedied in future testing by age-matched participant selection. Another possible issue is stratification of the severity of disease, as well as stratification based on joints affected. With a larger sample size and a more involved questionnaire, this limitation could be resolved.

There were also many strengths to this research. This research described a novel method for evaluating finger kinematics *in vivo*, which also introduced a novel set of palpable features for non-invasive digitization. This technique does not require line of sight and is not bulky to wear, resulting in it being very useful for examination of ADLs. The experimental protocol also was non-invasive and did not require any imaging to be completed. In the literature review, no research was found that was able to provide this combination of advantages.

The approach proposed in this research allows for patient specific definition of coordinate frames. This has an advantage when considering the deformity of finger segments that may occur with H-OA, which may cause the finger segments to become mal-aligned. The landmark approach allowed the method to consider this variation, and resulted in anatomically derived frames being used, capturing the pose of the deformed bony segments.

Another strength of this work was that it was possible to quantitatively measure joint range of motion in ADLs and examine the ADLs with and without JPP recommendations. Previously, no quantitative evaluation of JPP recommendations for the fingers has been found.

Six DoF EM trackers were used in this study, which always provided not only position but also orientation of each sensor. This was a strength that allowed for flexibility in the post-processing procedure, as well as information on sensor rotation with respect to the skin (roll) which was noted as a possible concern.

This approach also offered continuous, real time sampling, allowing for uninterrupted motion from the participant during functional tasks. This was advantageous as static or quasi-static performance of the tasks may have altered the kinematics and would have been difficult to train participants to do.

4.3   Future Directions

A major topic of interest would be to sensorize all the fingers and evaluate the performance of a more diverse set of ADLs. This would allow for a more complete understanding of the RoM requirements and interaction between digits in healthy and arthritic hands. The sample size would also need to be much higher than the sample presented in this work. This would help to better quantify *in vivo* finger kinematics and would assist in evaluating treatment options for these tasks (JPPs).

Combining kinematic measurement with force measurement techniques would be very useful. With combined kinematic and force data, it would be possible to identify quantitatively the tasks that require the most force and RoM and identify any patterns in these values. It would also be possible to examine the differences between healthy and arthritic joint force and the relationship of laxity to force output. This would inform recommendations on how to reduce the risk of permanent deformity of the finger joints for people with H-OA. This could lead to the development of a "profile" of tasks, and what joints are most important for each task, the RoM requirements, and alternatives (essentially

an updated JPP recommendations manual). This would allow for clinical recommendations to have more quantitative backing, which may help increase patient compliance and improve outcomes.

Another possible area of research is comparing the EM tracking technology to another measurement method (besides goniometry). The comparison could use 4DCT and involve real time performance of a limited number of tasks (constraints based on 4DCT capture area and type of task). This would allow for further, more in-depth analysis of the difference between the true bony RoM (osteokinematics) and the sensor reported RoM, as well as more in-depth investigation of skin motion effects.

Improvement of the EM system is another potential area of research. Creation of a wireless system would be useful, as currently the participant's ability to move around a room is limited by the sensor wire length. Work could also be done to provide a user facing program to show the joint RoM and the motion pathways in real time, eliminating the need for time consuming post-processing of the data. This would improve clinical viability and would allow for patients to immediately see the impacts of treatment methods such as JPPs being applied.

Conducting a study to examine the progression of H-OA may also be of interest in the future. By conducting RoM and task RoM evaluation of people with H-OA at multiple stages of the disease in a longitudinal study, the effects of the disease may be better understood. Another area of interest would be examining whether adherence to JPPs influences patient outcomes.

Another interesting area of study may be to look at finger involvement in tasks, and the relative importance of each digit. This may lead to increased information on which digits are easier to manage without, and which are key factors in performing ADLs effectively.

The technology and methods within this work could also be applied to other settings, such as other activities. An investigation into the kinematics of office work,

production line work, or sports could provide useful insight into repetitive or awkward actions. It may also be interesting to examine the effects of corrective measures on joint RoM, such as bracing, splints, or other treatments. Evaluation of the marketed finger joint implants mentioned in Chapter 1 would also be of interest.

4.4   Significance

This research presented a novel method of evaluating *in vivo* finger kinematics using 6 DoF EM tracking and a novel landmark coordinate system definition. It fills a gap in the literature, as studies have focused on examining functional tasks/ADLs[11,33,41,44,59] or the effect of joint degenerative diseases[16,59], but not usually both. Investigation of the effects of skin motion was also done on a cadaveric specimen. The results of this research provide a foundation and framework for evaluating *in vivo* finger kinematics in the future and presents potential research areas to pursue. The method proposed is applicable for use *in vivo*, shows that EM tracking is viable for finger kinematic tracking, and it is comparable to goniometer measurement of joint RoM of the thumb, index, and middle finger joints. This study also showed that health status affects joint RoM, and that use of JPPs for some tasks significantly changes the RoM needed in certain joints to perform them, in both healthy and arthritic subsets. This demonstrates that while there are important differences introduced by using JPPs, future efforts need to increase the sample size and standardize/categorize the way individuals perform tasks further.

References

1. Netter FH. *Atlas of Human Anatomy*. Third. Teterboro: ICON Learning Systems; 2003.

2. Nordin M, Frankel VH. *Basic Biomechanics of the Musculoskeletal System*. 3rd ed. Lippincott Williams & Wilkins; 2001.

3. Oatis CA. *Kinesiology: The Mechanics and Pathomechanics of Human Movement*. Second. Philadelphia, PA: Lippincott Williams & Wilkins; 2009.

4. Buczek FL, Sinsel EW, Gloekler DS, Wimer BM, Warren CM, Wu JZ. Kinematic performance of a six degree-of-freedom hand model (6DHand) for use in occupational biomechanics. *J Biomech*. 2011;44(9):1805-1809. doi:10.1016/j.jbiomech.2011.04.003

5. Goislard de Monsabert B, Visser JMA, Vigouroux L, Van der Helm FCT, Veeger HEJ. Comparison of three local frame definitions for the kinematic analysis of the fingers and the wrist. *J Biomech*. 2014;47(11):2590-2597. doi:10.1016/j.jbiomech.2014.05.025

6. Dumas R, Camomilla V, Bonci T, Chèze L, Cappozzo A. What Portion of the Soft Tissue Artefact Requires Compensation When Estimating Joint Kinematics? *J Biomech Eng*. 2015;137(6):064502. doi:10.1115/1.4030363

7. Cerveri P, De Momi E, Lopomo N, Baud-Bovy G, Barros RML, Ferrigno G. Finger Kinematic Modeling and Real-Time Hand Motion Estimation. *Ann Biomed Eng*. 2007;35(11):1989-2002. doi:10.1007/s10439-007-9364-0

8. Wu G, Van Der Helm FCT, Veeger HEJ, et al. ISB recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motion - Part II: Shoulder, elbow, wrist and hand. *J Biomech*. 2005;38(5):981-992. doi:10.1016/j.jbiomech.2004.05.042

9.   Coupier J, Hamoudi S, Telese-Izzi S, Feipel V, Rooze M, Van Sint Jan S. A novel method for in-vivo evaluation of finger kinematics including definition of healthy motion patterns. *Clin Biomech*. 2016;31:47-58. doi:10.1016/j.clinbiomech.2015.10.002

10.   Carpinella I, Mazzoleni P, Rabuffetti M, Thorsen R, Ferrarin M. Experimental protocol for the kinematic analysis of the hand: Definition and repeatability. *Gait Posture*. 2005;23(4):445-454. doi:10.1016/j.gaitpost.2005.05.001

11.   Bain GI, Polites N, Higgs BG, Heptinstall RJ, McGrath AM. The functional range of motion of the finger joints. *J Hand Surg Eur Vol*. 2015;40(4):406-411. doi:10.1177/1753193414533754

12.   Buffi JH, Crisco JJ, Murray WM. A method for defining carpometacarpal joint kinematics from three-dimensional rotations of the metacarpal bones captured in vivo using computed tomography. *J Biomech*. 2013;46:2104-2108. doi:10.1016/j.jbiomech.2013.05.019

13.   Nataraj R, Li Z. Robust identification of three-dimensional thumb and index finger kinematics with a minimal set of markers. *J Biomech Eng*. 2013;135(9):091002-1-091002-091009. doi:10.1115/1.4024753

14.   Luker KR, Aguinaldo A, Kenney D, Cahill-Rowley K, Ladd AL. Functional task kinematics of the thumb carpometacarpal joint. *Clin Orthop Relat Res*. 2014;472(4):1123-1129. doi:10.1007/s11999-013-2964-0

15.   Metcalf CD, Robinson R, Malpass AJ, et al. Markerless Motion Capture and Measurement of Hand Kinematics : Validation and Application to Home-Based Upper Limb Rehabilitation. *IEEE Trans Biomed Eng*. 2013;60(8):2184-2192. doi:10.1109/TBME.2013.2250286

16.   Leitkam ST, Bush TR. Comparison Between Healthy and Reduced Hand Function Using Ranges of Motion and a Weighted Fingertip Space Model. *J Biomech Eng*.

2015;137(April 2015). doi:10.1115/1.4029215

17.   Leitkam ST, Bush TR, Bix L. Determining Functional Finger Capabilities of Healthy Adults: Comparing Experimental Data to a Biomechanical Model. *J Biomech Eng*. 2014;136(2):021022. doi:10.1115/1.4026255

18.   Sancho-bru JL, Perez-Gonzalez A, Vergara-Monedero M, Giurintano D. A 3-D dynamic model of human finger for studying free movements. *J Biomech*. 2001;34:1491-1500.

19.   Sancho-bru JL, Mora MC, Leon BE, Perez-Gonzalez A, Iserte JL, Morales A. Grasp modelling with a biomechanical model of the hand. *Comput Methods Biomech Biomed Engin*. 2014;17(4):297-310. doi:10.1080/10255842.2012.682156

20.   Blana D, Chadwick EK, Van Den Bogert AJ, Murray WM. Engineering Real-time simulation of hand motion for prosthesis control. *Comput Methods Biomech Biomed Engin*. 2017;20:1-17. doi:10.1080/10255842.2016.1255943

21.   Barry AJ, Murray WM, Kamper DG. Development of a dynamic index finger and thumb model to study impairment. *J Biomech*. 2018;77:206-210. doi:10.1016/j.jbiomech.2018.06.017

22.   Ellis B, Bruton A. A study to compare the reliability of composite finger flexion with goniometry for measurement of range of motion in the hand. 2002:562-570.

23.   Welch G, Foxlin E. Motion tracking: No silver bullet, but a respectable arsenal. *IEEE Comput Graph Appl*. 2002;22(6):24-38. doi:10.1109/MCG.2002.1046626

24.   Magit DP, McGarry M, Tibone JE, Lee TQ. Comparison of cutaneous and transosseous electromagnetic position sensors in the assessment of tibial rotation in a cadaveric model. *Am J Sports Med*. 2008;36(5):971-977. doi:10.1177/0363546507312639

25. Tung WL, Kuo LC, Lai KY, Jou IM, Sun YN, Su FC. Quantitative evidence of kinematics and functional differences in different graded trigger fingers. *Clin Biomech*. 2010;25(6):535-540. doi:10.1016/j.clinbiomech.2010.02.009

26. Hassan EA, Jenkyn TR, Dunning CE. Direct comparison of kinematic data collected using an electromagnetic tracking system versus a digital optical system. *J Biomech*. 2007;40(4):930-935. doi:10.1016/j.jbiomech.2006.03.019

27. Ryu JH, Miyata N, Kouchi M, Mochimaru M, Lee KH. Analysis of skin movement with respect to flexional bone motion using MR images of a hand. *J Biomech*. 2006;39(5):844-852. doi:10.1016/j.jbiomech.2005.02.001

28. Dahaghin S, Bierma-Zeinstra SMA, Ginai AZ, Pols HAP, Hazes JMW, Koes BW. Prevalence and pattern of radiographic hand osteoarthritis and association with pain and disability (the Rotterdam study). *Ann Rheum Dis*. 2005;64(5):682-687. doi:10.1136/ard.2004.023564

29. Wang KK, Zhang X, McCombe D, Ackland DC, Ek ET, Tham SK. Quantitative analysis of in-vivo thumb carpometacarpal joint kinematics using four-dimensional computed tomography. *J Hand Surg Eur Vol*. 2018;43:1088-1097. doi:10.1177/1753193418789828

30. Kortier HG, Sluiter VI, Roetenberg D, Veltink PH. Assessment of hand kinematics using inertial and magnetic sensors. *J Neuroeng Rehabil*. 2014;11(1):70. doi:10.1186/1743-0003-11-70

31. de Vries WHK, Veeger HEJ, Cutti AG, Baten C, van der Helm FCT. Functionally interpretable local coordinate systems for the upper extremity using inertial & magnetic measurement systems. *J Biomech*. 2010;43(10):1983-1988. doi:10.1016/j.jbiomech.2010.03.007

32. Zhang X, Lee SW, Braido P. Determining finger segmental centers of rotation in flexion-extension based on surface marker measurement. *J Biomech*.

2003;36(8):1097-1102. doi:10.1016/S0021-9290(03)00112-X

33.   Gracia-Ibáñez V, Vergara M, Sancho-Bru JL, Mora MC, Piqueras C. Functional range of motion of the hand joints in activities of the International Classification of Functioning, Disability and Health. *J Hand Ther*. 2017;30(3):337-347. doi:10.1016/j.jht.2016.08.001

34.   Benoit DL, Damsgaard M, Andersen MS. Surface marker cluster translation , rotation , scaling and deformation : Their contribution to soft tissue artefact and impact on knee joint kinematics. *J Biomech*. 2015;48(10):2124-2129. doi:10.1016/j.jbiomech.2015.02.050

35.   Cereatti A, Bonci T, Akbarshahi M, et al. Standardization proposal of soft tissue artefact description for data sharing in human motion measurements. *J Biomech*. 2017;62:5-13. doi:10.1016/j.jbiomech.2017.02.004

36.   Hochman DJ, The Arhtritis Society. Osteoarthritis. 2017. https://arthritis.ca/about-arthritis/arthritis-types-(a-z)/types/osteoarthritis. Published 2017.

37.   Falconer J. Hand osteoarthritis. *J Hand Ther*. 2012;17(2):47-50. doi:10.1258/ht.2011.011025

38.   Arthritis Foundation. Arthritis By The Numbers. https://www.arthritis.org/Documents/Sections/About-Arthritis/arthritis-facts-stats-figures.pdf. Published 2018.

39.   Haugen IK, Englund M, Aliabadi P, et al. Prevalence, incidence and progression of hand osteoarthritis in the general population: The Framingham Osteoarthritis Study. *Ann Rheum Dis*. 2011;70(9):1581-1586. doi:10.1136/ard.2011.150078

40.   Amaral DS, Duarte ALBP, Barros SS, et al. Assistive devices: an effective strategy in non-pharmacological treatment for hand osteoarthritis—randomized clinical trial. *Rheumatol Int*. 2018;38(3):343-351. doi:10.1007/s00296-017-3892-1

41. Roda-sales A, Vergara M, Sancho-bru JL, Gracia-ibáñez V, Jarque-bou NJ. Effect of assistive devices on hand and arm posture during activities of daily living. *Appl Ergon*. 2019;76(December 2018):64-72. doi:10.1016/j.apergo.2018.12.003

42. Institute KK. Joint Protection Program Handbook.

43. Kroon FP, Rubio R, Schoones JW, Kloppenburg M. Intra-articular therapies in the treatment of hand osteoarthritis: a systematic literature review. *Osteoarthr Cartil*. 2015;24(2016):S520. doi:10.1016/j.joca.2016.01.952

44. Vergara M, Sancho-Bru JL, Gracia-Ib????ez V, P??rez-Gonz??lez A. An introductory study of common grasps used by adults during performance of activities of daily living. *J Hand Ther*. 2014;27(3):225-234. doi:10.1016/j.jht.2014.04.002

45. Reissner L, Schindele S, Hensler S, Marks M, Herren DB. Ten year follow-up of pyrocarbon implants for proximal interphalangeal joint replacement. *J Hand Surg Eur Vol*. 2014;39(6):582-586. doi:10.1177/1753193413511922

46. Richard MJ, Lunich JA, Correll GR. The use of the Artelon CMC Spacer for osteoarthritis of the basal joint of the thumb. *J Hand Ther*. 2014;27(2):122-126. doi:10.1016/j.jht.2013.12.001

47. Drayton P, Morgan BW, Davies MC, Giddins GEB, Miles AW. A biomechanical study of the effects of simulated ulnar deviation on silicone finger joint implant failure. *J Hand Surg Eur Vol*. 2016;41(9):944-947. doi:10.1177/1753193415603228

48. Ehrl D, Erne HC, Broer PN, Metz C, Falter E. Painful thumb carpometacarpal joint osteoarthritis : Results of a novel treatment approach. *J Plast Reconstr aesthetic Surg*. 2016;69(7):972-976. doi:10.1016/j.bjps.2016.02.005

49. McVeigh KH, Murray PM, Heckman MG, Rawal B, Peterson JJ. Accuracy and

Validity of Goniometer and Visual Assessments of Angular Joint Positions of the Hand and Wrist. *J Hand Surg Am*. 2016;41(4):e21-e35. doi:10.1016/j.jhsa.2015.12.014

50. Van Den Noort JC, Kortier HG, Beek N Van, Veeger DHEJ, Veltink PH. Measuring 3D hand and finger kinematics - A comparison between inertial sensing and an opto-electronic marker system. *PLoS One*. 2016;11(11):1-17. doi:10.1371/journal.pone.0164889

51. Coupier J, Moiseev F, Feipel V, Rooze M, Van Sint Jan S. Motion representation of the long fingers: A proposal for the definitions of new anatomical frames. *J Biomech*. 2014;47(6):1299-1306. doi:10.1016/j.jbiomech.2014.02.017

52. Jarque-Bou N, Gracia-Ibáñez V, Sancho-Bru JL, Vergara M, Pérez-González A, Andrés FJ. Using kinematic reduction for studying grasping postures. An application to power and precision grasp of cylinders. *Appl Ergon*. 2016;56:52-61. doi:10.1016/j.apergo.2016.03.003

53. Carpinella I, Jonsdottir J, Ferrarin M. Multi-finger coordination in healthy subjects and stroke patients: a mathematical modelling approach. *J Neuroeng Rehabil*. 2011;(April):19. http://www.jneuroengrehab.com/content/8/1/19.

54. Lee KS, Jung MC. Three-dimensional finger joint angles by hand posture and object properties. *Ergonomics*. 2016;59(7):890-900. doi:10.1080/00140139.2015.1108458

55. Kia M, Schafer K, Lipman J, et al. A Multibody Knee Model Corroborates Subject-Specific Experimental Measurements of Low Ligament Forces and Kinematic Coupling During Passive Flexion. *J Biomech Eng*. 2017;138(May 2016):051010-1-12. doi:10.1115/1.4032850

56. Duck TR, Dunning CE, Armstrong AD, Johnson JA, King GJW. Application of screw displacement axes to quantify elbow instability. *Clin Biomech*.

2003;18(4):303-310. doi:10.1016/S0268-0033(03)00021-4

57.   Haddara M. Development of an Active Finger Motion Simulator : With In-Vitro Assessments of Tendon Loads and Joint Kinematics. 2018. https://ir.lib.uwo.ca/etd/5143.

58.   Chang CW, Kuo LC, Jou IM, Su FC, Sun YN. Artefact-reduced kinematics measurement using a geometric finger model with mixture-prior particle filtering. *Comput Methods Biomech Biomed Engin*. 2013;16(8):861-872. doi:10.1080/10255842.2011.643467

59.   Reissner L, Fischer G, List R, Giovanoli P, Calcagni M. Assessment of hand function during activities of daily living using motion tracking cameras : A systematic review. *J Eng Med*. 2019:20. doi:10.1177/0954411919851302

60.   Biggs J, Horch K. A three-dimensional kinematic model of the human long finger and the muscles that actuate it. *Med Eng Phys*. 1999;21(9):625-639. doi:10.1016/S1350-4533(99)00095-8

61.   Halilaj E, Rainbow MJ, Got C, et al. In vivo kinematics of the thumb carpometacarpal joint during three isometric functional tasks. *Clin Orthop Relat Res*. 2014;472(4):1114-1122. doi:10.1007/s11999-013-3063-y

62.   Stansfield B, Rooney S, Brown L, Kay M, Spoettl L, Shanmugam S. Gait & Posture Distal upper limb kinematics during functional everyday tasks. *Gait Posture*. 2018;61(December 2017):135-140. doi:10.1016/j.gaitpost.2018.01.004

63.   Bush TR, Bix L, Bello N, Fair J. Differences in the Kinematics of Restrained and Unrestrained Conditions of Opening for Two Sizes of Glass Jar. *Pack Technol Sci*. 2013;26:105-113. doi:10.1002/pts

64.   Gracia-Ibáñez V, Sancho-Bru JL, Vergara M. Relevance of grasp types to assess functionality for personal autonomy. *J Hand Ther*. 2018;31(1):102-110.

doi:10.1016/j.jht.2017.02.003

65. Edwards S, Buckland D, McCoy Powlen J. *Developmental & Functional Hand Grasps*. SLACK Incorporated; 2002.

66. MacDermid JC, Turgeon T, Richards RS, Beadle M, Roth JH. Patient Rating of Wrist Pain and Disability : A Reliable and Valid Measurement Tool. *J Orthop Trauma*. 1998;12(November 1998):577-586. https://ovidsp-dc2-ovid-com.proxy1.lib.uwo.ca/sp-3.33.0b/ovidweb.cgi.

67. The Patient-Rated Wrist Evaluation (PRWE) User Manual June 2011. 2011;(June).

68. Kato M, Echigo A, Ohta H, Ishiai S. For The Accuracy of Goniometric Measurements of Proximal Interphalangeal Joints in Fresh Cadavers : Comparison between Methods of Measurement , Types of Goniometers , and Fingers. *J Hand Ther*. 2007:12-19. doi:10.1197/j.jht.2006.11.015

69. White J, Coppola L, Skomurski A, Mitchell-Rekrut E. Influence of age and gender on normative passive range of motion values of the carpometacarpal joint of the thumb. *J Hand Ther*. 2018;31(3):390-397. doi:10.1016/j.jht.2017.02.011

Appendices

Appendix A: Iterations of 3D printed dorsal finger mount
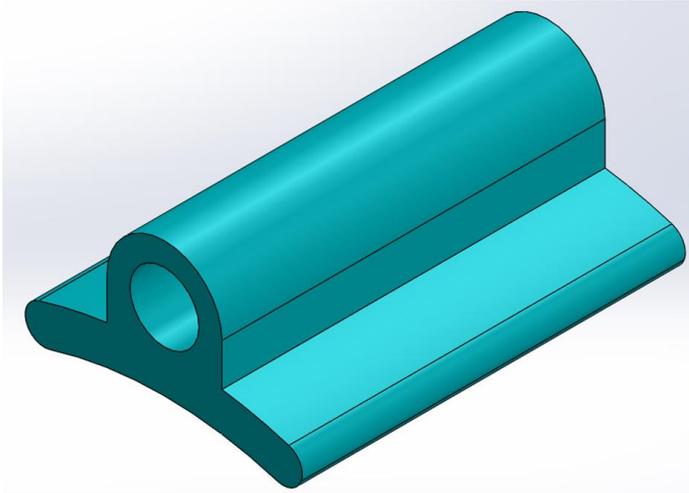
Version 1
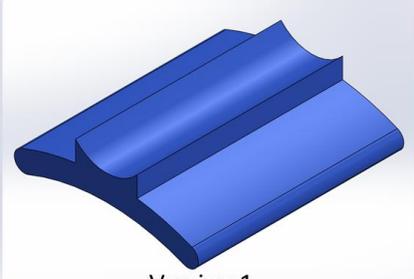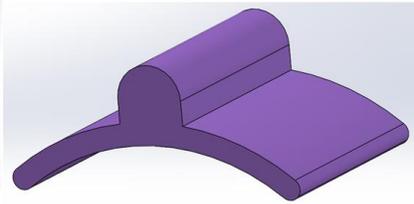
Version 2

Version 3

Appendix B: *In vivo* participant test protocol

Examination of motion patterns *in vivo* during activities of daily living

Purpose: To measure and examine motion patterns (joint excursion, joint deformity) of participants performing various activities of daily living (ADLs).

Protocol:

Pre-Test:

1. Day before: Set up apparatus and ensure it is functioning (program runs, all sensors are working, all tasks are present and accounted for, fastening materials are not running low).

Setup:

2. Check software and sensors again to ensure they are working.
3. Plug in all sensors accordingly to small tag labels to ensure proper placement.
4. Instruct participant to sit comfortably and to position hand palm down on a flat desk.
5. Determine which mount curvatures to use for each segment of the finger.
6. Place trackers in each mount, ensuring that they do not rotate within the mount. Use adhesive to secure them if they are loose.
7. Mount EM trackers to hand (start at distal phalange of finger, then proceed proximally).
   a. Placed on surface of volar side of the phalanges. EM tracker long axis in line with long axis of the finger and attached to the surface with medical adhesive and medical tape.
   b. Place a metacarpal sensor on the third metacarpal, again in line with long axis of finger.
   c. Ensure participant is unrestricted during motion of hands and wrist joint. Adjust slack if necessary.
8. Secure loose wires to the participant's hand/wrist using self-stick tape as necessary.

Landmark Digitization:

Ensure that during each landmark digitization, the participant remains as still as possible. They may move between digitizations though.

9. Perform the landmark digitization protocol following the landmark guide provided.
10. Record any problems/anomalies during this, such as difficulty locating landmarks or sensor movement.

Calibration/Check:

11. Ask participant to keep hand inside working bounds at all times. This is not a problem given
12. Instruct participant to perform a series of basic motions as indicated below. Each task is to be repeated 3 times, at a constant, slow speed. Begin recording data before each task. Use a goniometer for measurements at the extremes of motion.
    a. Flexion/extension of the 4 fingers, starting with flexion.
    b. Flexion/Extension of the thumb, starting with flexion.

Testing:

13. Set up the task to be performed in the test area in front of the participant.
14. Explain the task.
15. Tasks are to be performed according to the test sheet, with data being recorded each time (separate data sets for each task run). The participant will perform each task 2 times their natural way and 2 times with JPP practises involved. Tasks (9) are as follows:
    a. Write a sentence.
    b. Open water bottle.
    c. Squeeze spray bottle.
    d. Turn standard tap on/off.
    e. Turn lever tap on/off.
    f. Do up and undo a snap.
    g. Do up and undo a button on a shirt
    h. Unlock a doorknob with key (place in keyhole, twist, pull out).
    i. Plug in/unplug toaster
16. Repeat starting from step 13 until all tasks are completed.

Clean-up:

17. Ensure all data was collected appropriately and all files saved correctly.
18. Remove all sensors and fastening material from participant.
19. Clean up cords and sensors neatly.
20. Thank participant, compensate for help.
21. Clean up task materials and work area.

Appendix C: *In vitro* **joint range of motion using a hand motion simulator (Table)**

	IND DIP			IND PIP			RING DIP			RING PIP		
In Vitro Flexion/Extension (Degrees)												
	Bone	Skin	Difference	Bone	Skin	Difference	Bone	Skin	Difference	Bone	Skin	Difference
Avg	78	79	4	78	82	5	86	89	6	70	77	7
StdDev	17	17	3	14	14	4	11	11	4	12	13	4
In Vitro Varus/Valgus (Degrees)												
	Bone	Skin	Difference	Bone	Skin	Difference	Bone	Skin	Difference	Bone	Skin	Difference
Avg	21	17	6	21	21	5	29	30	5	24	16	8
StdDev	8	6	5	5	6	3	6	5	4	12	4	12
In Vitro Internal/External Rotation (Degrees)												
	Bone	Skin	Difference	Bone	Skin	Difference	Bone	Skin	Difference	Bone	Skin	Difference
Avg	21	18	5	20	19	5	21	23	5	19	15	5
StdDev	6	7	3	6	5	3	5	7	4	4	4	4

Appendix D: Mannequin hand proof of concept testing

Mannequin Hand Test

To look for errors introduced by the matrix manipulation and post-processing protocol during testing, a proof of concept validation was conducted with a wooden mannequin hand. This experiment is done with both the "bone" and "skin" mounted trackers rigidly fixed to the rigid bodies to simulate an ideal case of no skin motion.

The test was conducted using two adjacent wooden segments across the DIP joint of the index finger. Four sensors were attached to the segments, two medial-lateral ones inserted for the bone 'perpendicular' sensors, and two mounted on the dorsal side of the finger to simulate the skin 'parallel' sensors (Figure 27). Digitizations were performed as per the protocol used in the *in vivo* testing. Finally, 10 flexion/extension trials were performed, with manual goniometer measurements taken at full flexion and full extension. The operator in this test was the same as the operator for the *in vivo* testing outlined in section 2. For these trials, the adhesive used was electrical tape, as the medical adhesive used *in vivo* did not adhere well to the wooden components.
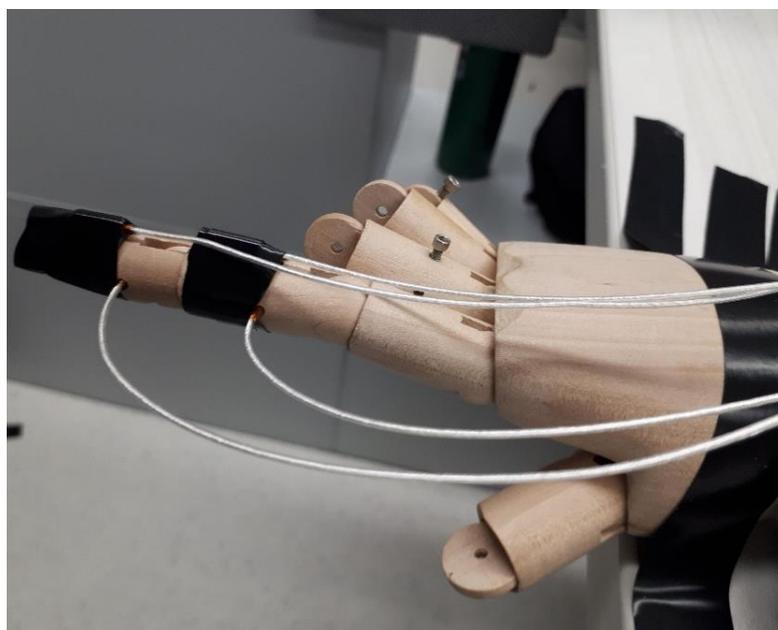
Figure 27: Mannequin hand setup

Sensors placed in the mannequin hand were press fit into the holes, drilled in the same manner as in the cadaveric testing.

Data Analysis

Bone mounted EM, skin mounted EM, and goniometer reported RoM were examined for homogeneity of variance using Levene's Test (SPSS v25, SPSS Inc, Chicago, IL). A one-way MANOVA statistical test was conducted for the Bone mounted EM, skin mounted EM, and goniometer reported RoM. Linear regression was done for each pair to look at correlation, and Bland Altmann plots were constructed.

Results

Mean absolute difference (SD) of the total RoMs for the mannequin finger joint during Flex/Ext motion are presented in Table 13. For flexion/extension motion, differences in joint angle were found between bone trackers and goniometer values (4°(4)), skin trackers and goniometer values (3°(2)), and bone trackers and skin trackers (5°(6)). The differences between bone trackers and skin trackers for varus/valgus motion (3°(2)) and for internal/external motion (4°(4)) was also found. A visual comparison of the goniometer, skin mount, and bone mount reported values is presented in Figure 28.

Table 13: Absolute differences between skin mounted trackers, bone mounted trackers, and goniometer measurements in the mannequin hand test

Mannequin Hand Flexion/Extension Motion (Degrees)					
	Flexion/Extension			Varus/Valgus	Internal/External
Trial	G - B	G - S	B - S	B - S	B - S
1	0	3	3	6	7
2	5	5	10	2	8
3	3	4	1	2	3
4	4	1	3	1	2
5	4	3	1	1	3
6	1	2	1	6	3
7	2	7	5	3	2
8	14	6	20	2	12
9	5	2	3	4	2
10	1	1	0	6	0
Avg	4	3	5	3	4
StdDev	4	2	6	2	4
B - Bone G - Goniometer S - Skin					
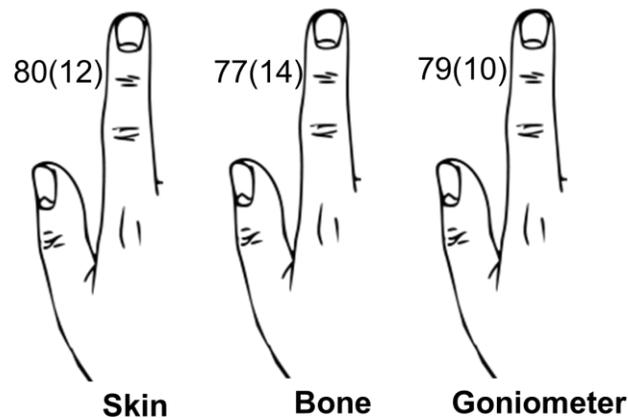
Figure 28: RoM for mannequin hand
Comparison of skin mounted, bone mounted, and goniometer measured flexion/extension.

No significant differences were found between bone EM and goniometry (p=0.892, 95% CI [-1.1, 6.1]), bone EM and skin EM (p=0.779, 95% CI [-8.6, 1.2]), and skin EM and goniometry (p=0.974, 95% CI [-4.0, 1.6]). Linear correlation between measurements was good for bone EM and goniometer ($R^2 = 0.89$) , bone EM and skin EM ($R^2 = 0.76$) , and skin EM and goniometer ($R^2 = 0.89$) pairs.

Bland-Altmann plots of the mannequin hand Flex/Ext data are presented in Figure 29, Figure 30, and Figure 31. There is no clear pattern of the spread of the data increasing or decreasing as joint RoM increases. The mean difference between measurement methods was 2.5° (bone EM and goniometer), -1.2° (skin EM and goniometer), and -3.7° (bone EM and skin EM).
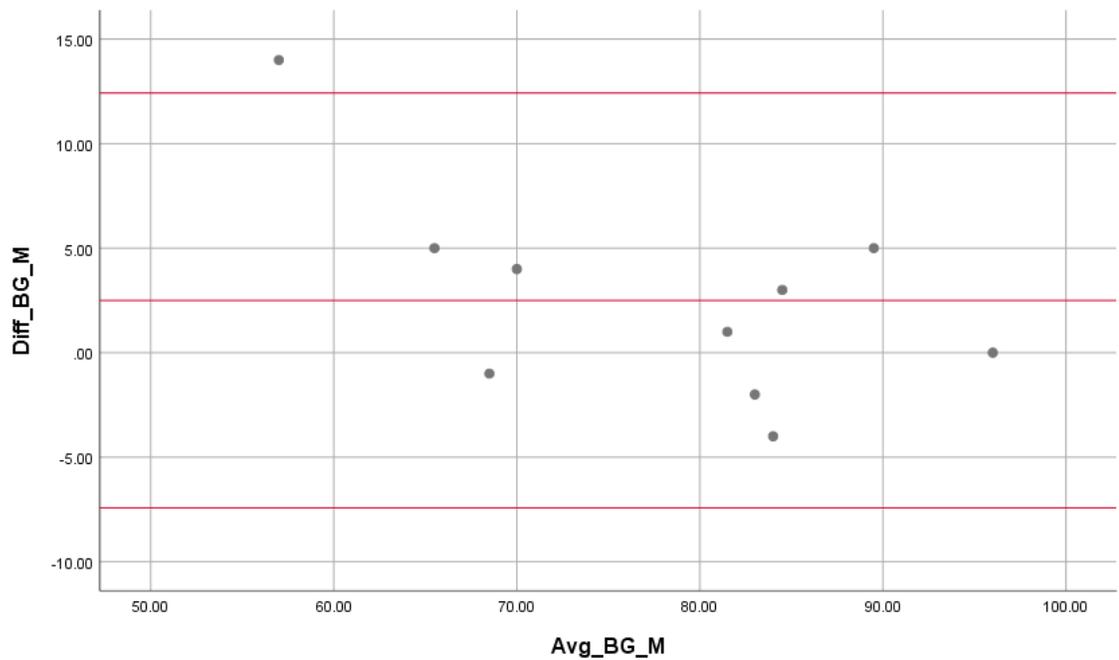
Figure 29: Bland-Altmann plot of the difference between bone EM tracking and goniometer RoM in the mannequin hand test
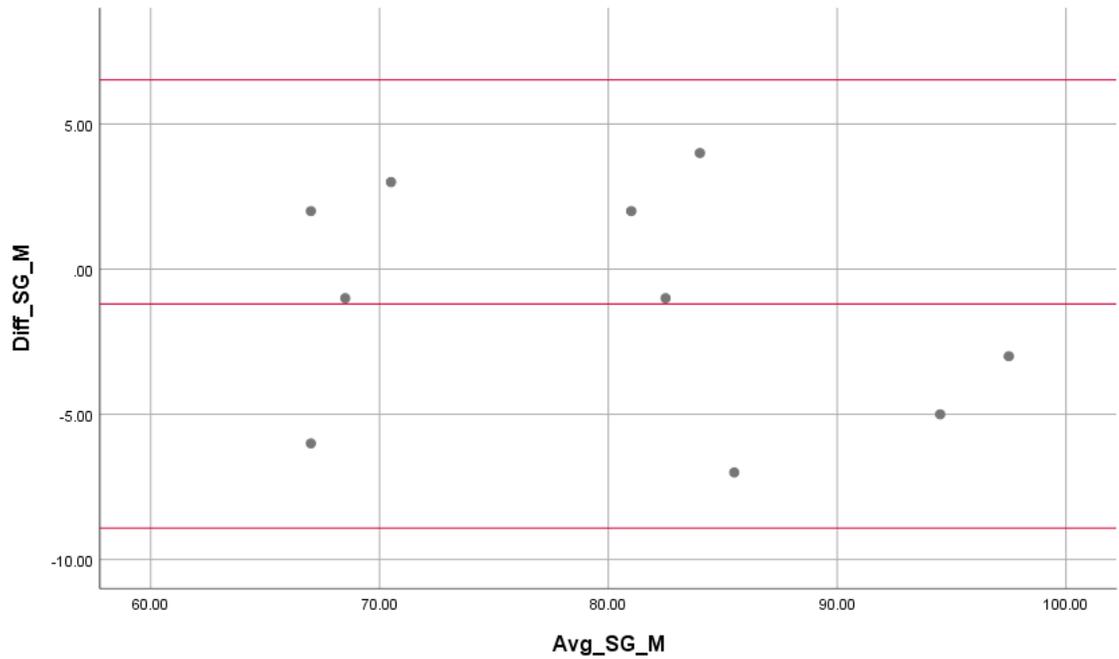
Figure 30: Bland-Altmann plot of the difference between skin EM tracking and goniometer RoM in the mannequin hand test
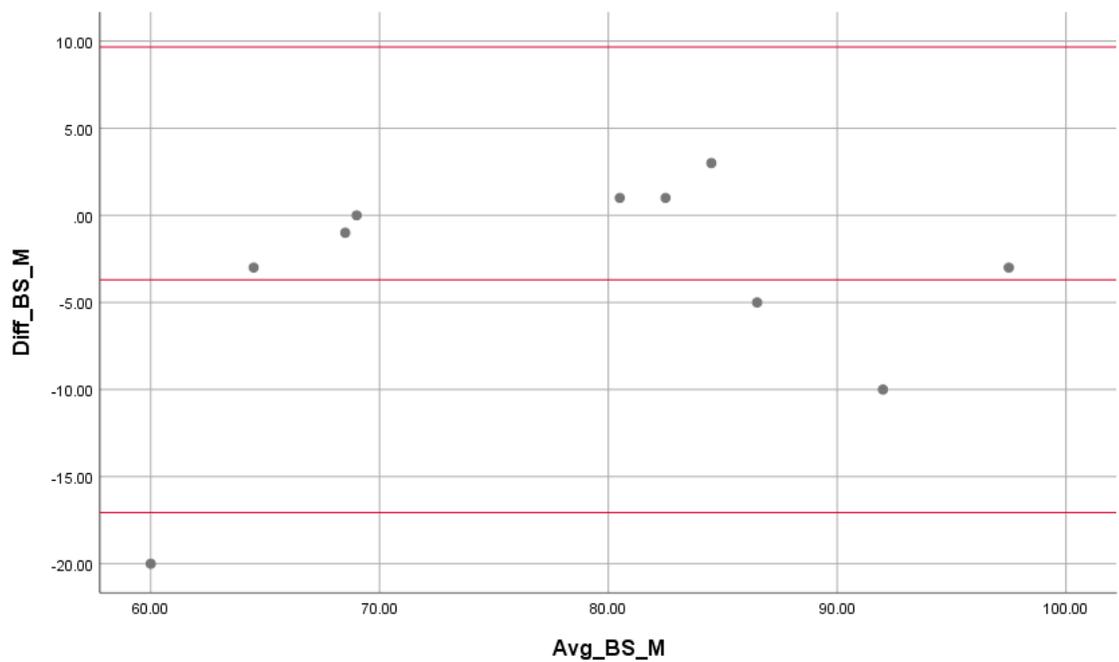
Figure 31: Bland-Altmann plot of the difference between bone EM tracking and skin EM tracking RoM in the mannequin hand test

Appendix E: Repeatability of generated coordinate system frames

Apparatus

The data acquisition system utilized in this experiment was the 3D Guidance TrakSTAR electromagnetic tracking system (Ascension Technologies). This experiment's system consisted of three data acquisition boxes synced to one medium range electromagnetic transmitter. A total of 11 sensors were utilized, 10 of which were attached to finger segments of the test subject, and the final one being used for digitization. 3D printed finger mounts were utilized for each sensor (except for the digitization sensor). To attach the sensors to the skin, the equipment outlined in section 2.2 was used.

Experimental Procedure

One participant (24, M) was equipped with ten mounted EM trackers across the thumb, index, and middle fingers of the dominant hand (right). Once secured with medical adhesive and medical tape, digitization was performed using an EM tracker inserted into a stylus. The participant was asked to place their hand on the table, thumb facing upwards. Digitization began on the thumb, proceeding sequentially as described in Section 2.4.2. The participant was then asked to place their hand palm down on the table, with some space between each finger. Sequential digitization was then performed on the index and middle finger segments. This process was repeated five times. Sensors were removed the adhesive was taken off using an adhesive remover. Landmark location and Euler angles between the skin mounted trackers and the associated landmark coordinate system were calculated.

Experiment Results

Table 14 shows the mean absolute difference (SD) of five repetitions of the digitization protocol on one test subject (M,24). These differences were calculated for the coordinate system origin and pose of the axis. Displacement differences ranged from 0±0mm to 3±2mm (x), from 1±0mm to 2±1mm (y), from 1±0mm to 3±1mm (z), from 3°±1 to 7°±4 (γ), from 2°±1 to 9°±6 (β), and from 3°±3 to 9°±6 (α).

Table 14: Repeatability of *in vivo* landmark digitization protocol

		x (mm)		y (mm)		z (mm)		gamma (°)		beta (°)		alpha (°)	
		Avg	Stddev	Avg	Stddev	Avg	Stddev	Avg	Stddev	Avg	Stddev	Avg	Stddev
FI	Distal Phalanx	1	(1)	1	(1)	3	(1)	7	(2)	2	(1)	9	(5)
	Proximal Phalanx	1	(1)	2	(1)	1	(1)	7	(4)	3	(2)	6	(3)
	Metacarpal	1	(1)	1	(1)	1	(1)	5	(4)	7	(5)	3	(3)
FII	Distal Phalanx	1	(0)	1	(0)	1	(0)	4	(4)	5	(3)	5	(4)
	Middle Phalanx	0	(0)	1	(1)	1	(1)	3	(1)	6	(4)	5	(4)
	Proximal Phalanx	1	(0)	1	(0)	1	(0)	4	(3)	6	(4)	6	(5)
FIII	Distal Phalanx	1	(0)	1	(1)	1	(0)	4	(3)	9	(6)	9	(6)
	Middle Phalanx	1	(1)	1	(0)	1	(1)	3	(1)	6	(5)	9	(5)
	Proximal Phalanx	2	(0)	1	(1)	1	(1)	5	(4)	7	(4)	8	(4)
	Metacarpal	3	(2)	2	(1)	2	(2)	3	(2)	6	(5)	6	(5)

Repeatability of Coordinate Frame Pose *In Vivo*

Appendix F: *In vivo* electromagnetic tracking hand evaluation data collection sheets

EM Tracking Hand Evaluation

Study ID:	
Date:	

Basic Motions (Recorded in Degrees, not time, use a manual goniometer):

Task	Trial 1		Trial 2		Trial 3	
Flex/Ext of the fingers, beginning with flexion.	Start	End	Start	End	Start	End
	Ind PIP	Ind PIP	Ind PIP	Ind PIP	Ind PIP	Ind PIP
	Ind DIP	Ind DIP	Ind DIP	Ind DIP	Ind DIP	Ind DIP
	Mid MCP	Mid MCP	Mid MCP	Mid MCP	Mid MCP	Mid MCP
	Mid PIP	Mid PIP	Mid PIP	Mid PIP	Mid PIP	Mid PIP
	Mid DIP	Mid DIP	Mid DIP	Mid DIP	Mid DIP	Mid DIP
Flex/Ext of thumb, starting with flexion	Start	End	Start	End	Start	End
	Th CMC	Th CMC	Th CMC	Th CMC	Th CMC	Th CMC
	Th MCP	Th MCP	Th MCP	Th MCP	Th MCP	Th MCP
	Th IP	Th IP	Th IP	Th IP	Th IP	Th IP

J.P. Tasks	Run 1 (natural)		Run 2 (natural)		Run 3 (JPP)		Run 4 (JPP)	
1. Push in plug and pull plug out								
2. Unlock a key (place in to unlock and pull the key out)								
3. Squeeze a spray bottle								
4. Open a water bottle								
5. Undo and do up a snap								
6. Turn lever tap on and off								
7. Turn standard tap on and off								
8. Do up a button on shirt and undo button								
9. Write a sentence								

List of tasks:

1. Push in plug of toaster and pull plug out
    a. Run 1 & 2 – naturally
    b. Run 3 & 4 – use 3 fingers to grip
2. Squeeze a spray bottle and release
    a. Run 1 & 2 – naturally
    b. Run 3 & 4 – use multiple fingers
3. Open a water bottle
    a. Run 1 & 2 - naturally
    b. Run 3 & 4 – use assistive device
4. Undo and do up a snap (thumb on top)
5. Turn lever tap on and of
    a. Run 1 & 2 - naturally
6. Turn standard tap on and off
    a. Run 1 & 2 – naturally
    b. Run 3 & 4 – flat palm rather than grip
7. Unlock a key (place in to unlock and then pull the key out)
    a. Run 1 & 2 - naturally
    b. Run 3 & 4 – use assistive device (blue handle)
8. Do up a button on a shirt and undo button
    a. Run 1 & 2 - naturally
    b. Run 3 & 4 – use assistive device
9. Write a sentence
    a. Run 1 & 2 – regular pen
    b. Run 3 & 4 – built up pen

Appendix G: *In vitro* finger motion simulator protocol

Comparison of Surface Mount and Bone Mount EM Tracking Methods

Purpose:

To evaluate the viability of surface mounted electromagnetic trackers for the study of in-vivo finger kinematics. This comparison looks at bone mounted EM trackers and compares skin mounted EM trackers against it. It also examines a method for digitizing surface landmarks for bony coordinate system definition, and to look at the flexion/extension and varus/valgus motions.

Protocol:

Pre-Test:

1. Day before: Set up apparatus and ensure it is functioning (program runs, motor controlled properly, all sensors are working).
2. Identify and thaw cadaver hand, record ID number.
3. Check CT of hand for degeneration.

Setup/Specimen Preparation:

4. Isolate flexor and extensor tendons for the index, middle, ring, and pinky fingers.
5. Suture the tendons with available suture (0-Vicryl).
6. Mount specimen onto simulator.
7. Drill holes in the Medial-Lateral direction for the index and ring finger phalanges (proximal, middle, and distal on the middle fingers) for EMG trackers.
8. Drill holes at 45° to the M-L direction in the finger phalanges (proximal, middle, and distal on the middle fingers) for EMG trackers.
9. Check software, motors, and sensors again to ensure function.
10. Attach all FDP flexors to one actuator and all FDS flexors to another and all extensors to a 3rd actuator.
11. Test motor control with tendons attached.

Testing:

12. Irrigate regularly throughout.

Bone mounted and skin mounted on 2 fingers (with metacarpal reference)

Sensor attachment and Landmark digitization protocol:

13. Attach bone and skin mounted sensors to the distal, middle, and proximal segments of the index and middle fingers. Attach another pair to the middle metacarpal (skin sensor on the metacarpal, bone is in the metacarpal bones).
14. Using digitization sensor, perform the landmark digitization as outlined by the protocol document. Save each landmark separately in the data collection.

Calibration/Check:

15. Perform a test cycle to determine extension and flexion, confirmed by surgeon/fellow.

Continuous

16. With system at extension, begin recording data in software (ensure data has a file path it is saving to).
17. Initiate flexion, wait for system to stabilize.
18. Initiate extension, wait for system to stabilize.
19. Repeat until tracker system has stopped recording for the designated window (1 minute).
20. Repeat steps 16-19 until at least 15 trials have been collected

Attach skin and bone mounted trackers to the ring finger, repeat steps 14-20 above

Cleanup:

1. Ensure all data was recorded appropriately.
2. Detach tendons and all sensors from hand.
3. Power down test devices appropriately.
4. Clean sensors.
5. Dispose of/refreeze cadaver hand.
6. Check all sensors and related devices for damage.
7. Clean up work area thoroughly.
8. Clean sensors thoroughly using hand sanitizer, soap, and disposable Lysol wipes (in that order). Clean the cords as well as the sensor itself, clean up until the silver connector to the DAQ.

Appendix H: Graphical representation of joint RoM (SD) comparison between healthy participants and participants with H-OA
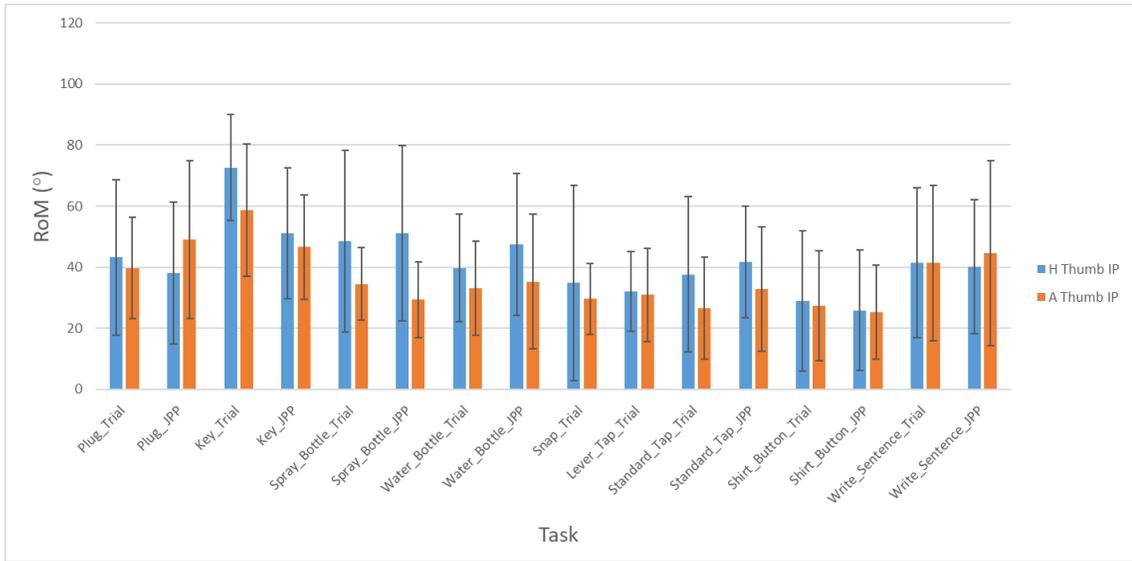
Figure 32: Thumb IP joint Flex/Ext RoM (SD)
Comparison across tasks for healthy participants and participants with arthritis (* denotes significant differences from healthy).
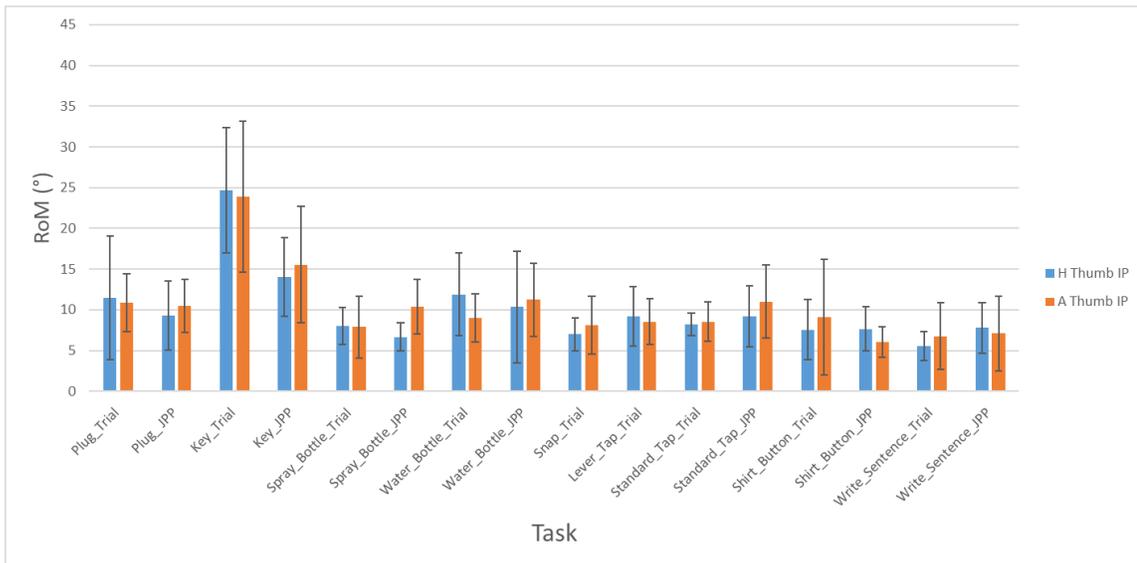
Figure 33: Thumb IP joint Abd/Add RoM (SD)
Comparison across tasks for healthy participants and participants with arthritis (* denotes significant differences from healthy).
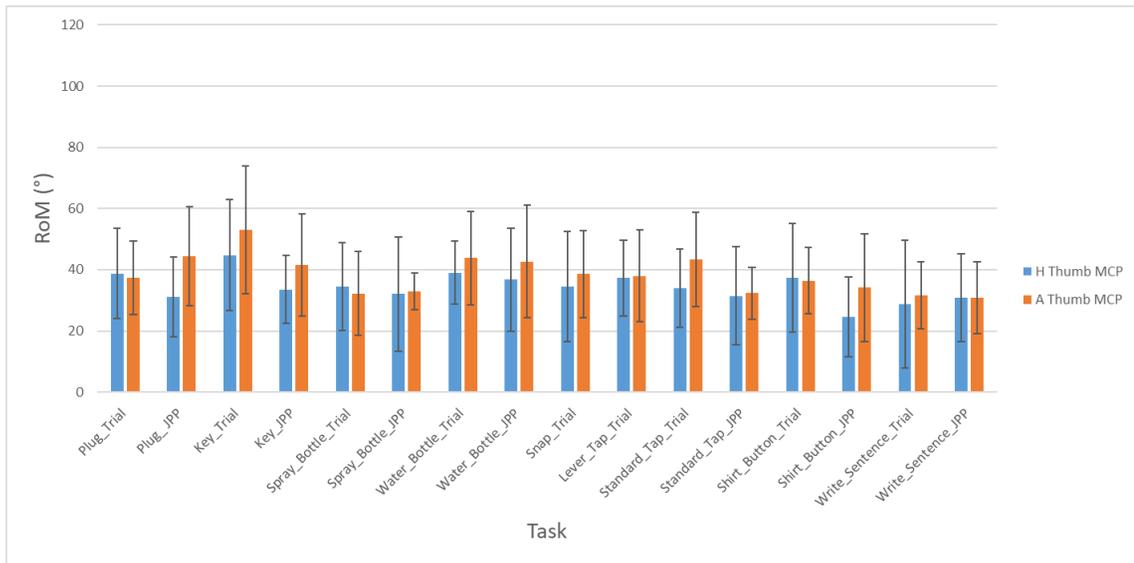
Figure 34: Thumb MCP joint Flex/Ext RoM (SD)
Comparison across tasks for healthy participants and participants with arthritis (* denotes significant differences from healthy).
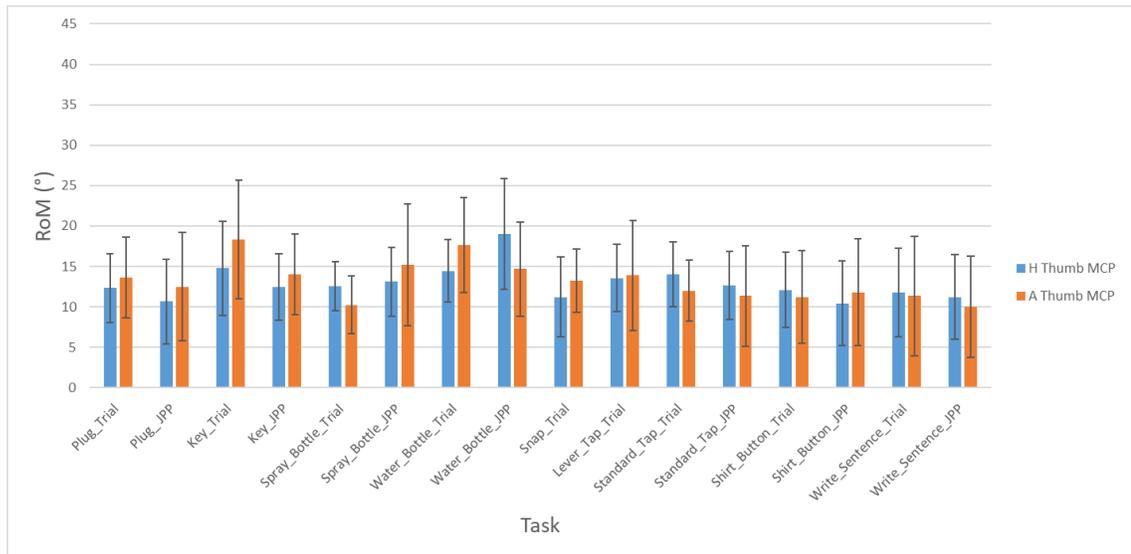
Figure 35: Thumb MCP joint Abd/Add RoM (SD)
Comparison across tasks for healthy participants and participants with arthritis (* denotes significant differences from healthy).
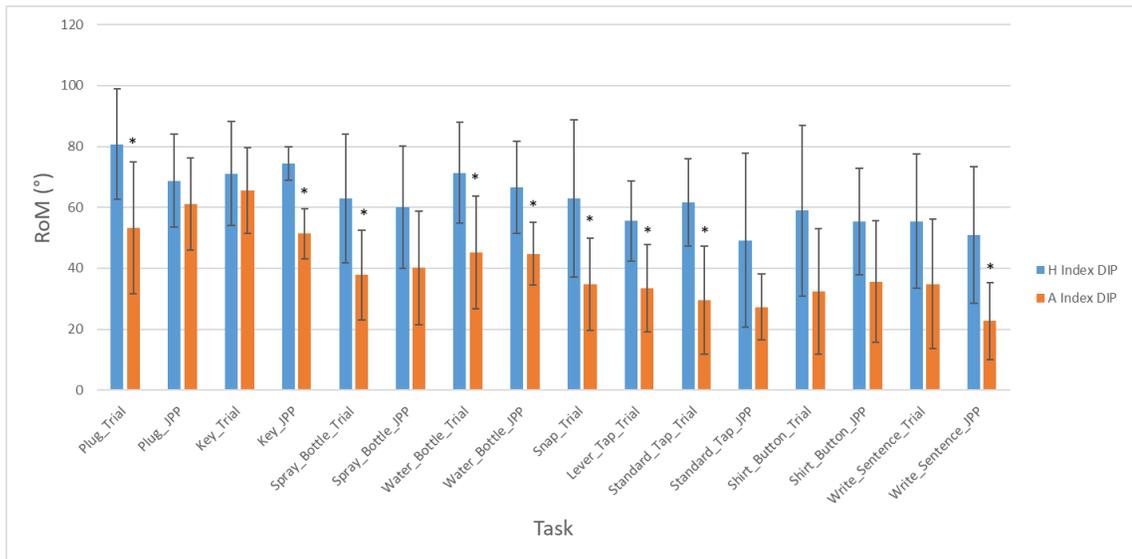
Figure 36: Index DIP joint Flex/Ext RoM (SD)
Comparison across tasks for healthy participants and participants with arthritis (denotes significant differences from healthy).*
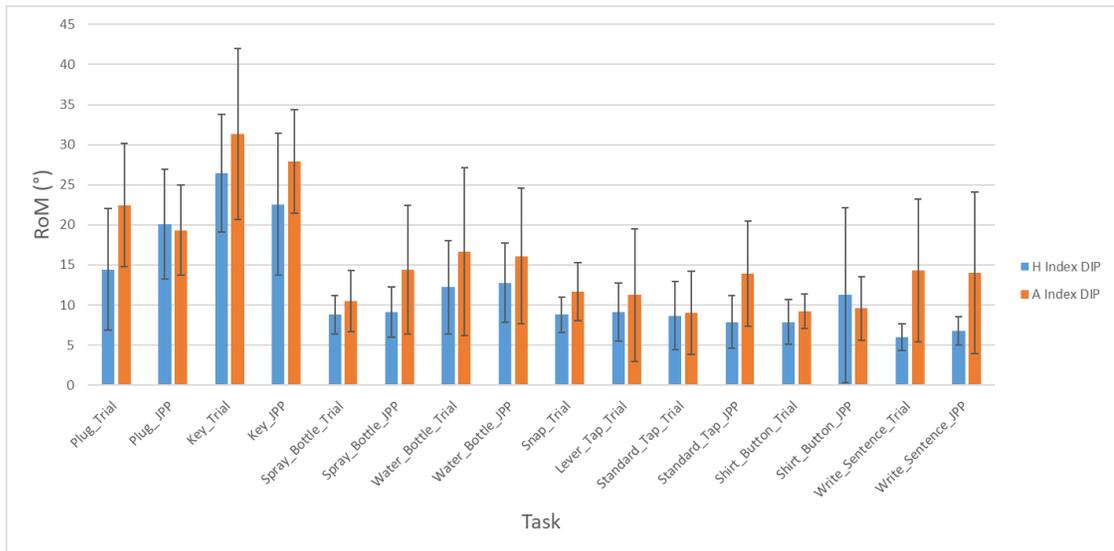
Figure 37: Index DIP joint Abd/Add RoM (SD)
Comparison across tasks for healthy participants and participants with arthritis (denotes significant differences from healthy).*
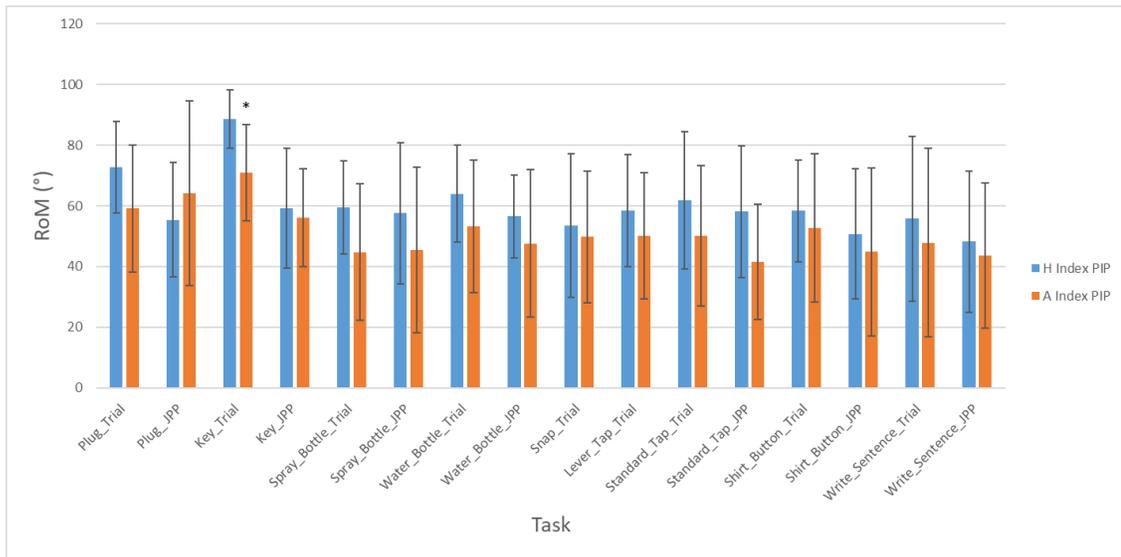
Figure 38: Index PIP joint Flex/Ext RoM (SD)
Comparison across tasks for healthy participants and participants with arthritis (denotes significant differences from healthy).*
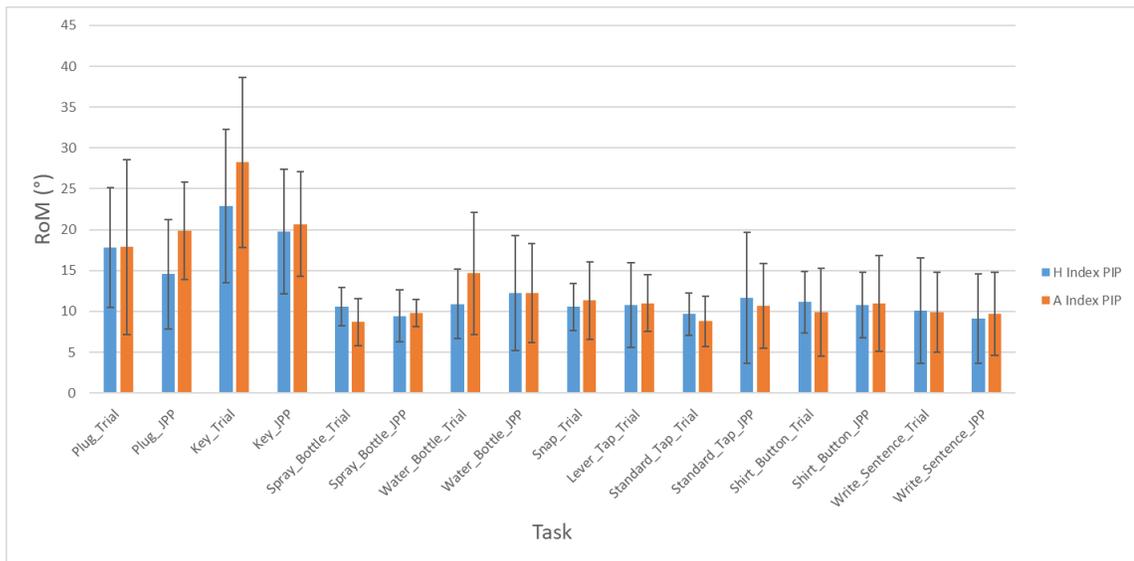
Figure 39: Index PIP joint Abd/Add RoM (SD)
Comparison across tasks for healthy participants and participants with arthritis (denotes significant differences from healthy).*
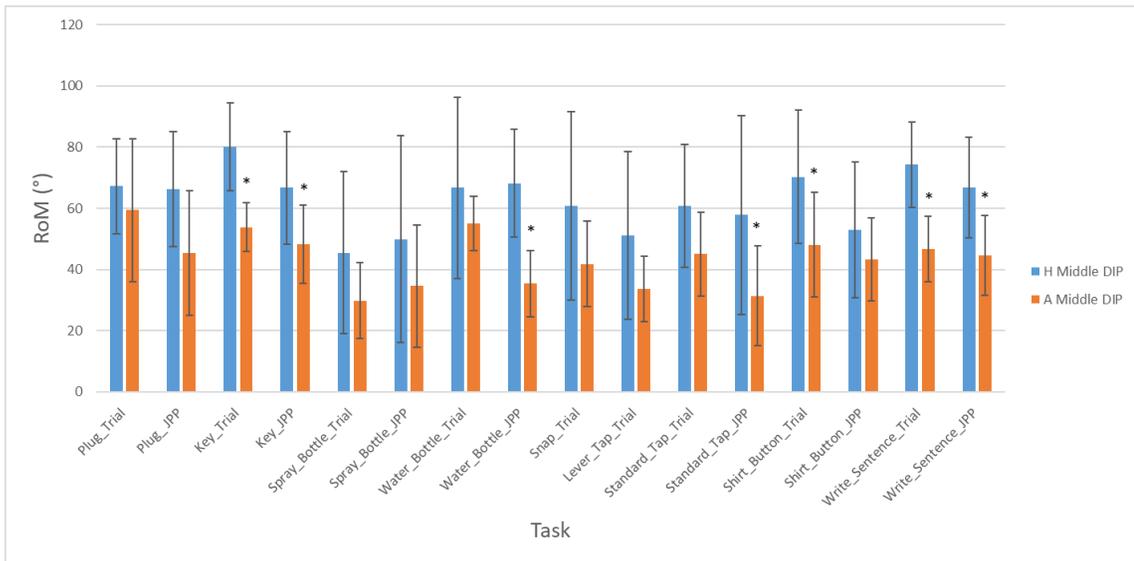
Figure 40: Middle DIP joint Flex/Ext RoM (SD)
Comparison across tasks for healthy participants and participants with arthritis (* denotes significant differences from healthy).
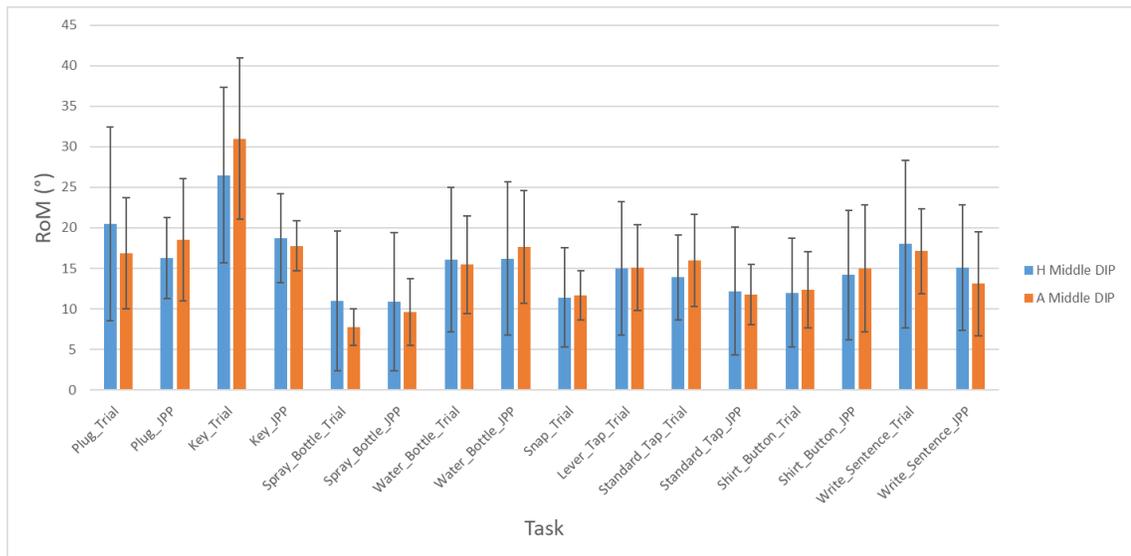
Figure 41: Middle DIP joint Abd/Add RoM (SD)
Comparison across tasks for healthy participants and participants with arthritis (* denotes significant differences from healthy).
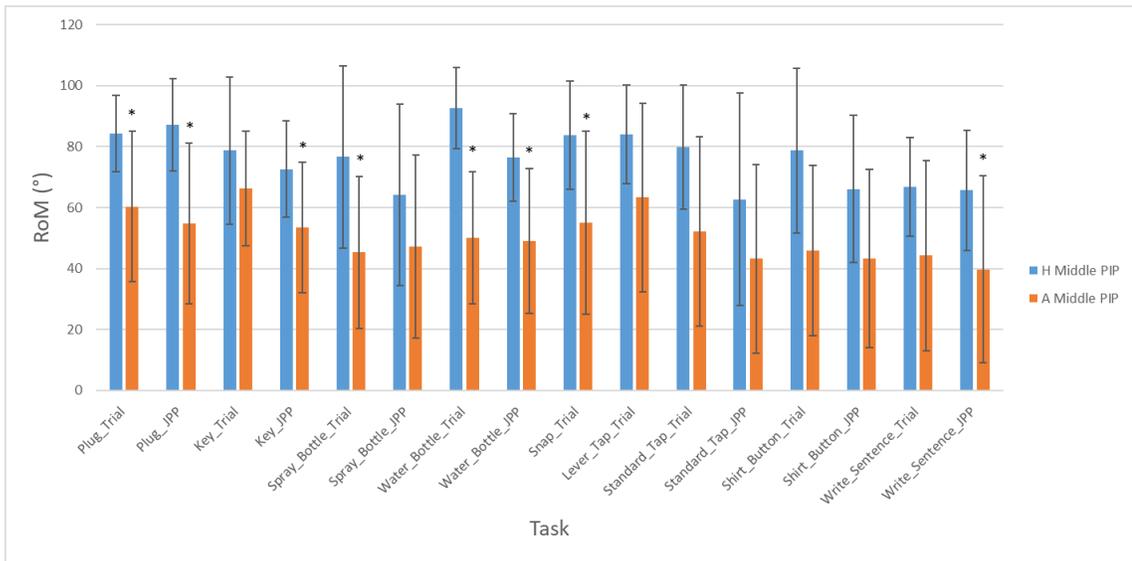
Figure 42: Middle PIP joint Flex/Ext RoM (SD)
Comparison across tasks for healthy participants and participants with arthritis (denotes significant differences from healthy).*
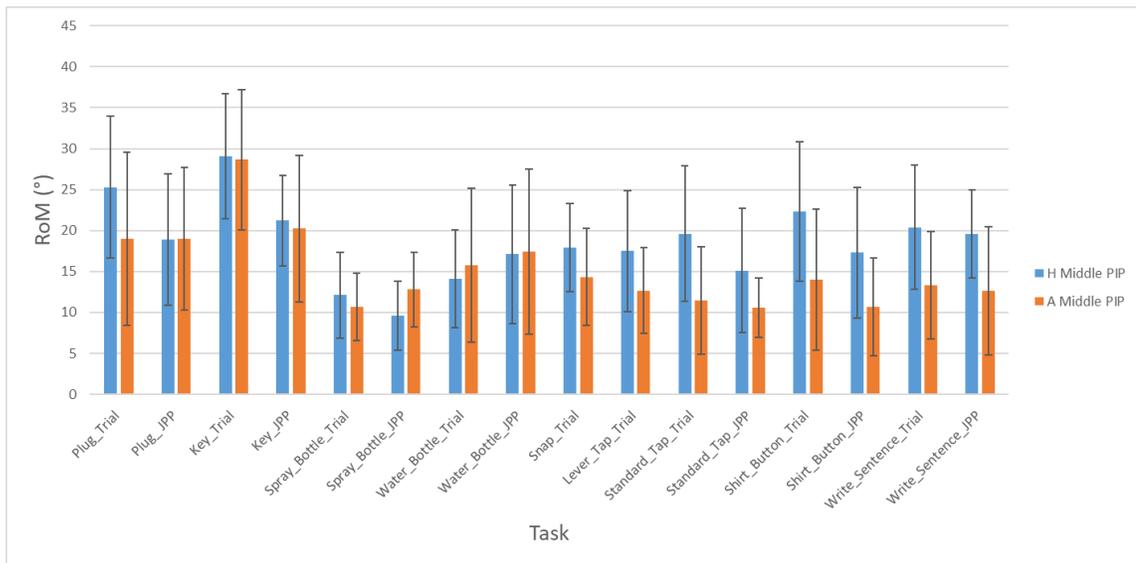
Figure 43: Middle PIP joint Abd/Add RoM (SD)
Comparison across tasks for healthy participants and participants with arthritis (denotes significant differences from healthy).*

Appendix I: Difference in joint RoM between healthy participants and participants with H-OA
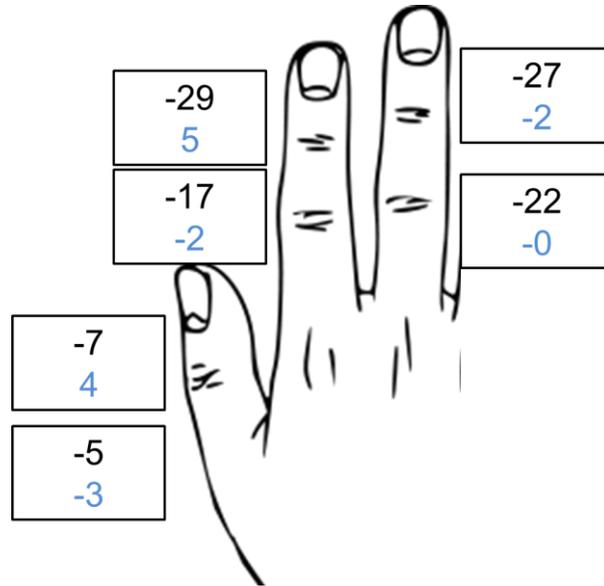
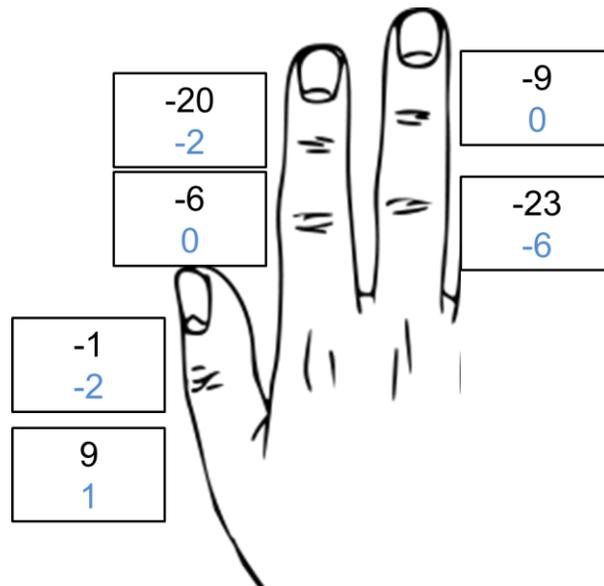**Figure 44: Difference in Flex/Ext (black) and Abd/Add (blue) for the basic flexion/extension motion**
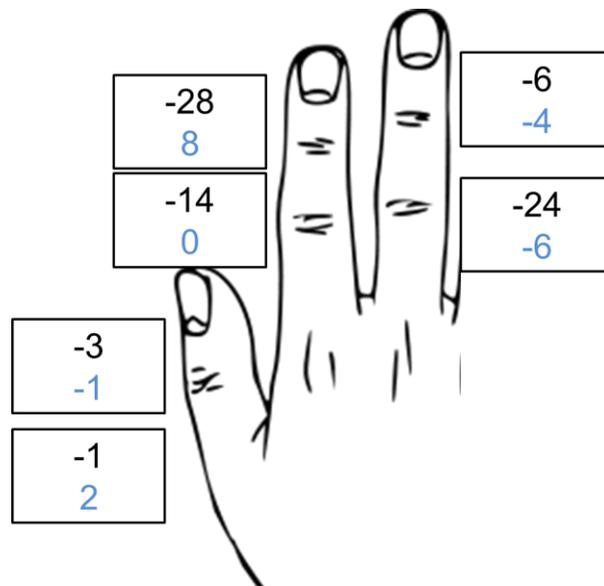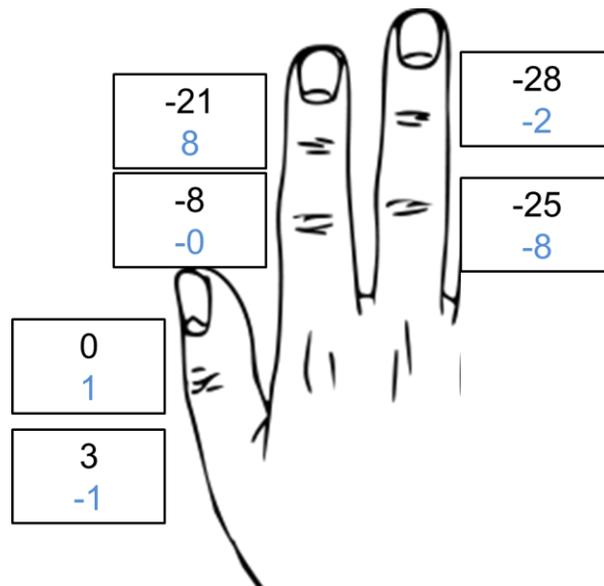

Figure 45: Difference in Flex/Ext (black) and Abd/Add (blue) for the plug task
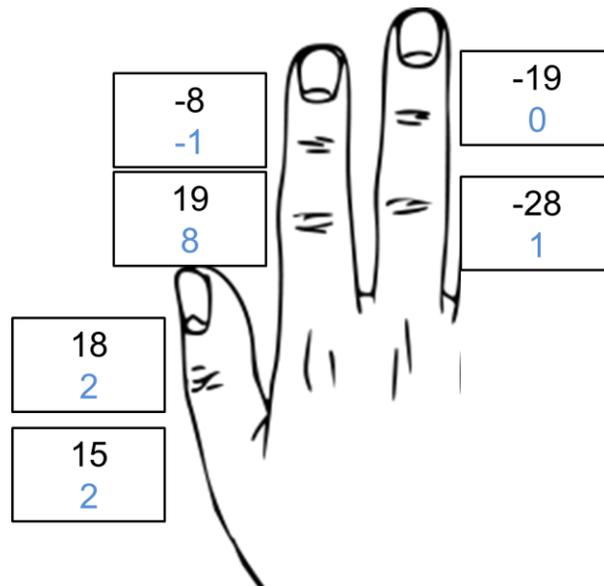
Figure 46: Difference in Flex/Ext (black) and Abd/Add (blue) for the plugjpp task
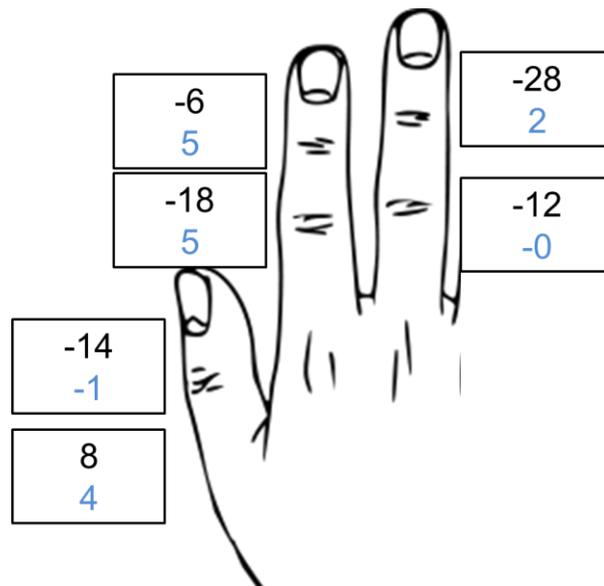
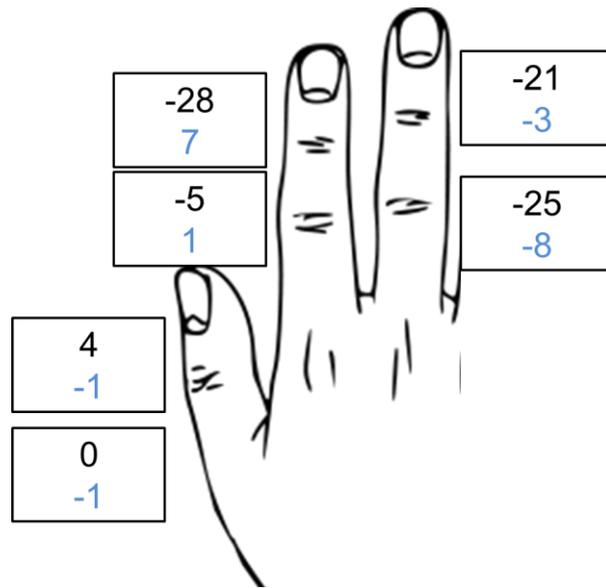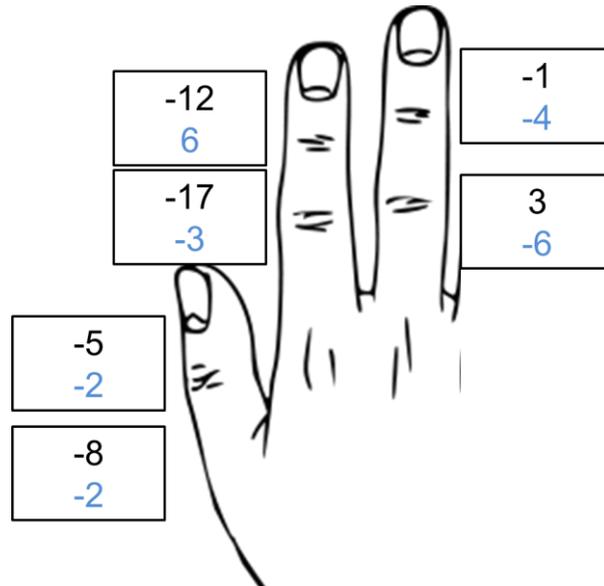**Figure 47: Difference in Flex/Ext (black) and Abd/Add (blue) for the key task**
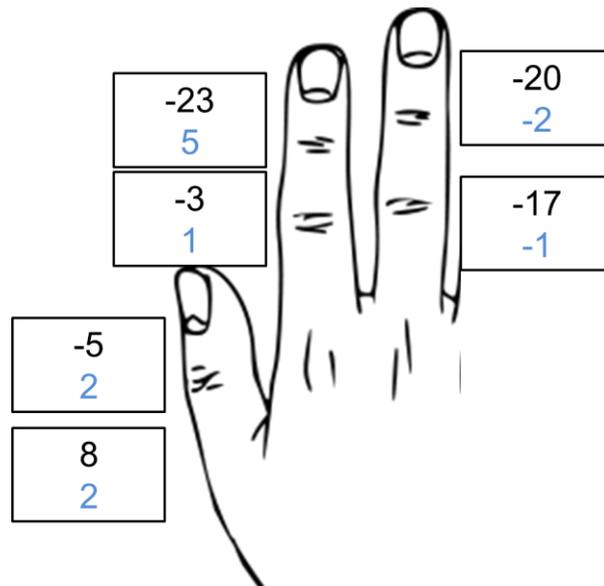
Figure 48: Difference in Flex/Ext (black) and Abd/Add (blue) for the keyjpp task
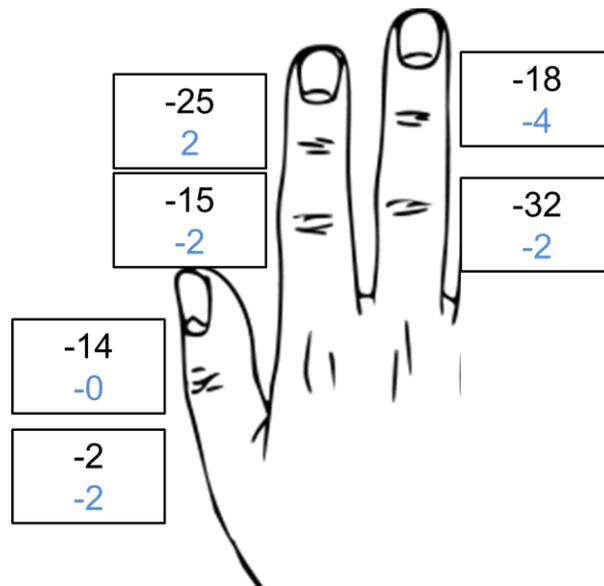
Figure 49: Difference in Flex/Ext (black) and Abd/Add (blue) for the spray bottle task
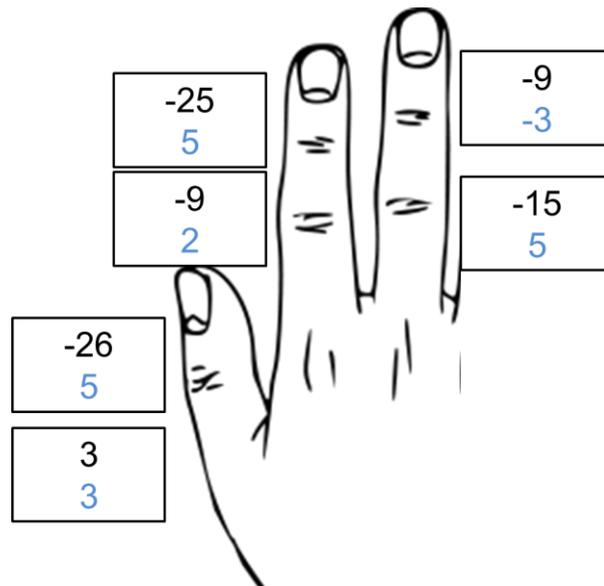
Figure 50: Difference in Flex/Ext (black) and Abd/Add (blue) for the spray bottlejpp task
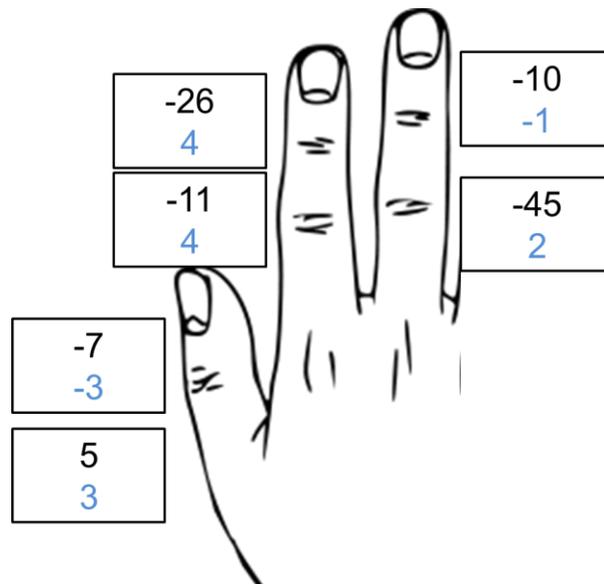
Figure 51: Difference in Flex/Ext (black) and Abd/Add (blue) for the bottle task
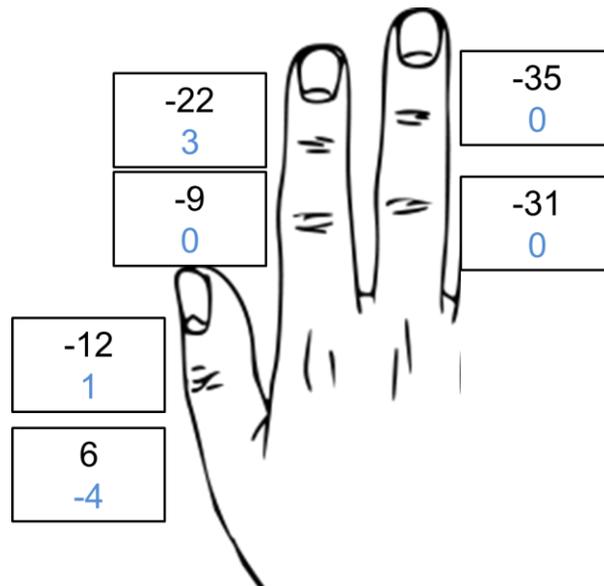
Figure 52: Difference in Flex/Ext (black) and Abd/Add (blue) for the bottlejpp task
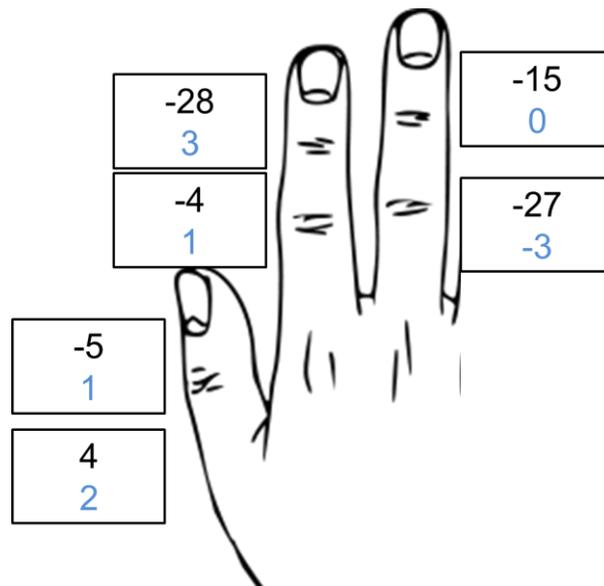
Figure 53: Difference in Flex/Ext (black) and Abd/Add (blue) for the snap task
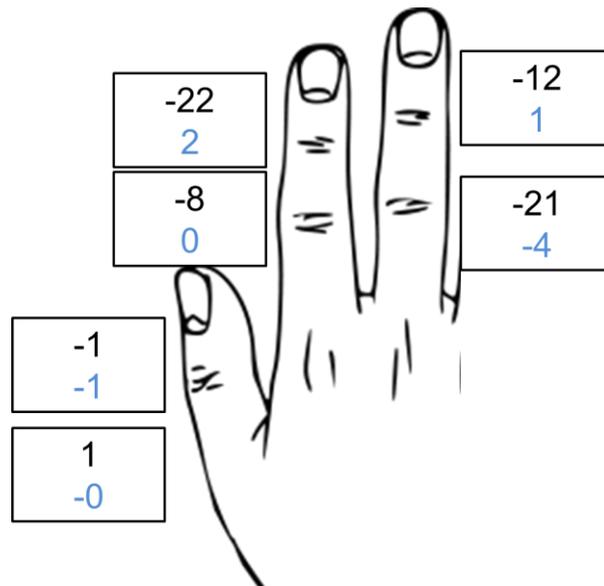
Figure 54: Difference in Flex/Ext (black) and Abd/Add (blue) for the lever tap task
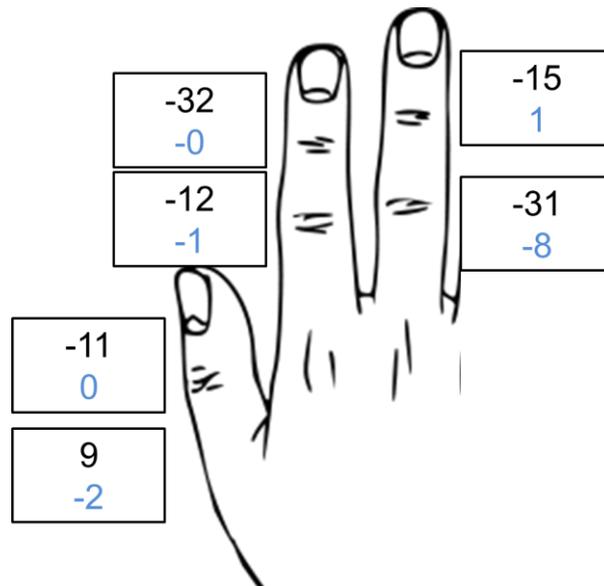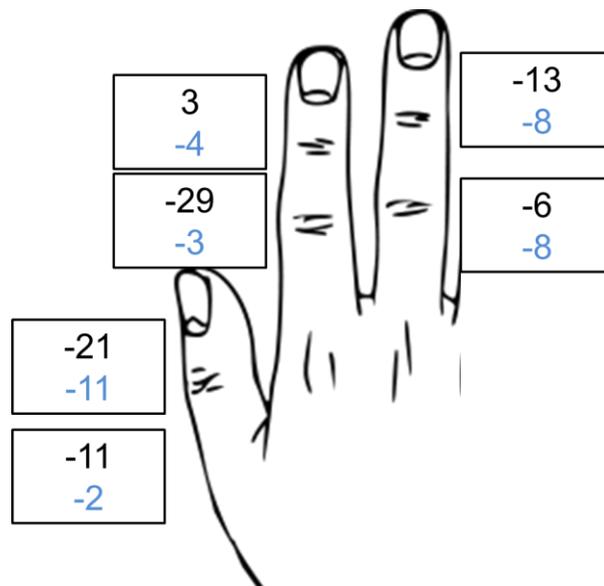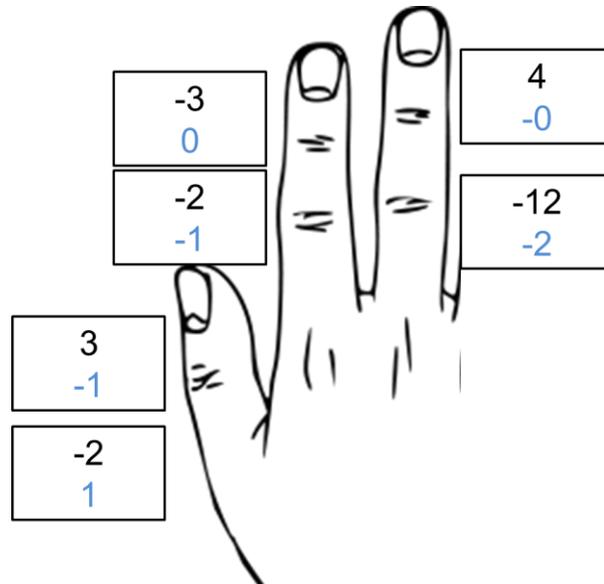

Figure 55: Difference in Flex/Ext (black) and Abd/Add (blue) for the tap task
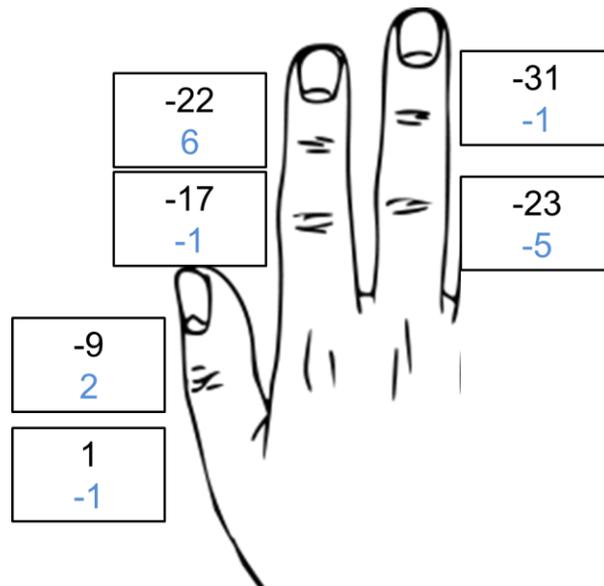
Figure 56: Difference in Flex/Ext (black) and Abd/Add (blue) for the tapjpp task
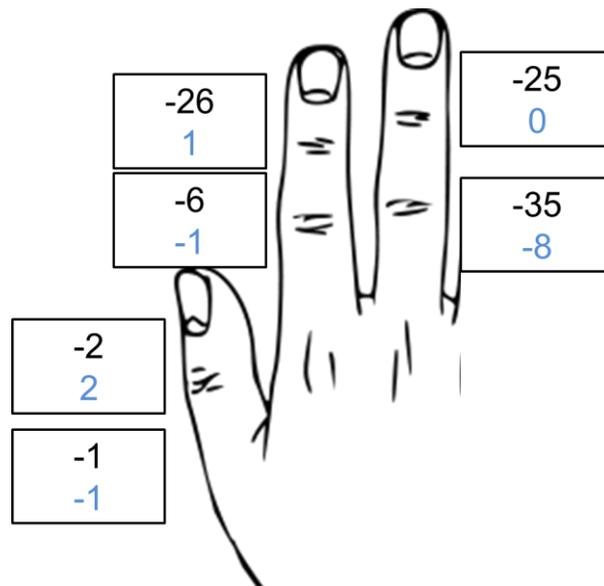
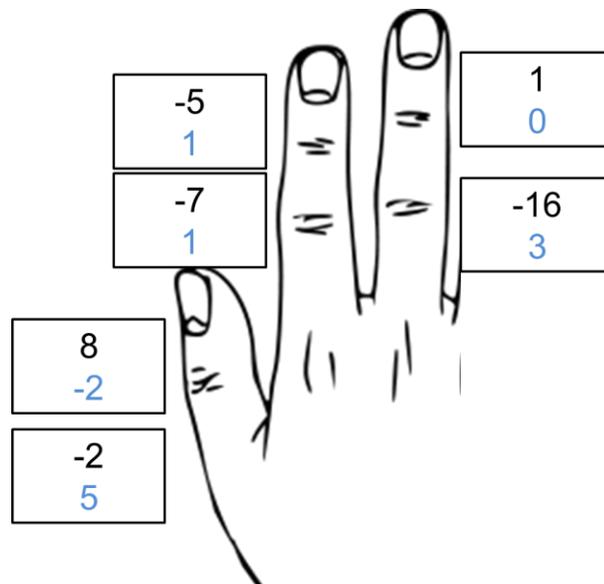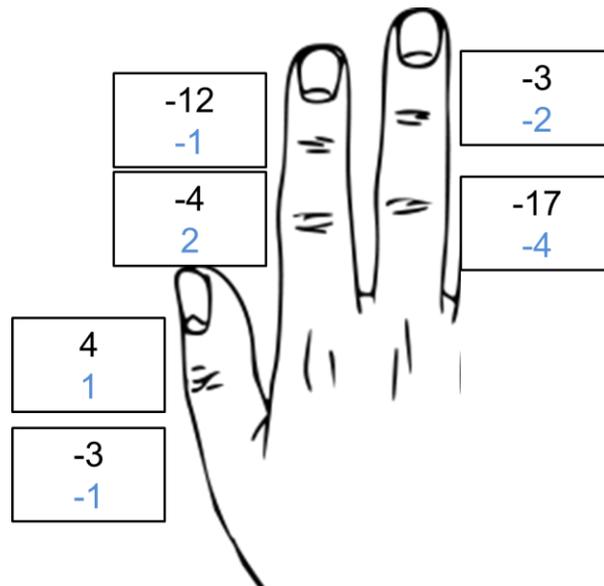
Figure 57: Difference in Flex/Ext (black) and Abd/Add (blue) for the button task

Figure 58: Difference in Flex/Ext (black) and Abd/Add (blue) for the buttonjpp task

Figure 59: Difference in Flex/Ext (black) and Abd/Add (blue) for the sentence task

Figure 60: Difference in Flex/Ext (black) and Abd/Add (blue) for the sentencejpp task

Appendix J: RoM differences in healthy participants performing tasks normally and with JPP recommendations
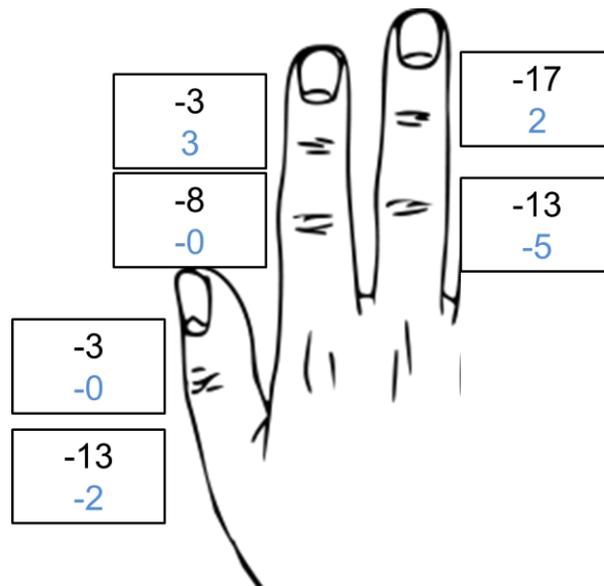

Figure 61: Difference in Flex/Ext (black) and Abd/Add (blue) for the plug task

Figure 62: Difference in Flex/Ext (black) and Abd/Add (blue) for the key task

Figure 63: Difference in Flex/Ext (black) and Abd/Add (blue) for the spray bottle task

Figure 64: Difference in Flex/Ext (black) and Abd/Add (blue) for the bottle task

Figure 65: Difference in Flex/Ext (black) and Abd/Add (blue) for the tap task

Figure 66: Difference in Flex/Ext (black) and Abd/Add (blue) for the button task
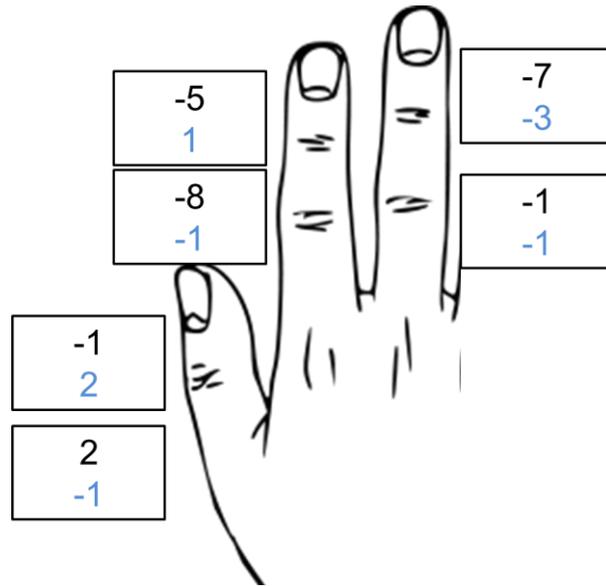
Figure 67: Difference in Flex/Ext (black) and Abd/Add (blue) for the sentence task

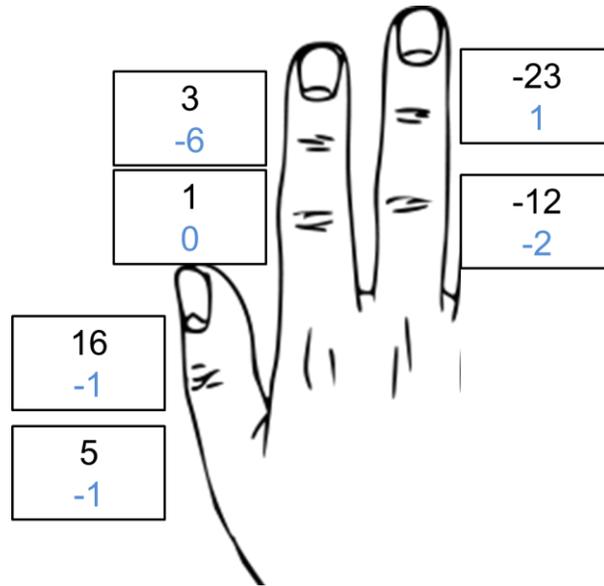**Appendix K: RoM differences in participants with hand osteoarthritis performing tasks normally and with JPP recommendations**

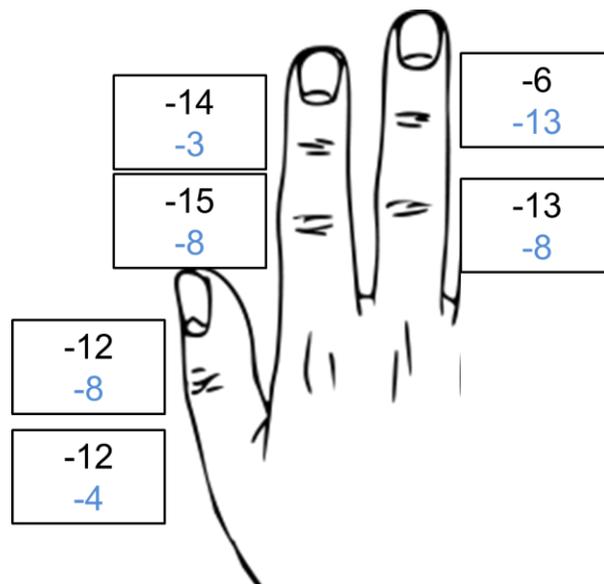**Figure 68: Difference in Flex/Ext (black) and Abd/Add (blue) for the plug task**

Figure 69: Difference in Flex/Ext (black) and Abd/Add (blue) for the key task
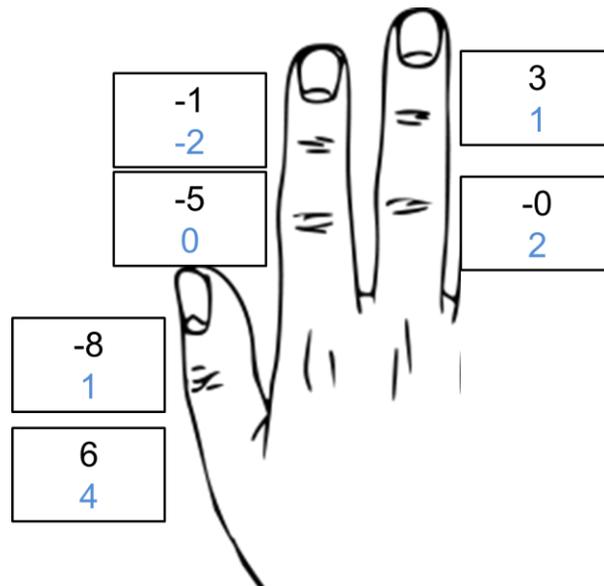
Figure 70: Difference in Flex/Ext (black) and Abd/Add (blue) for the spray bottle task
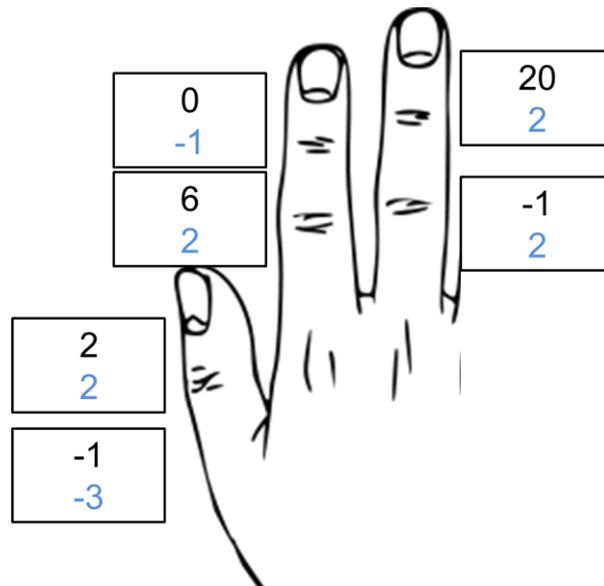

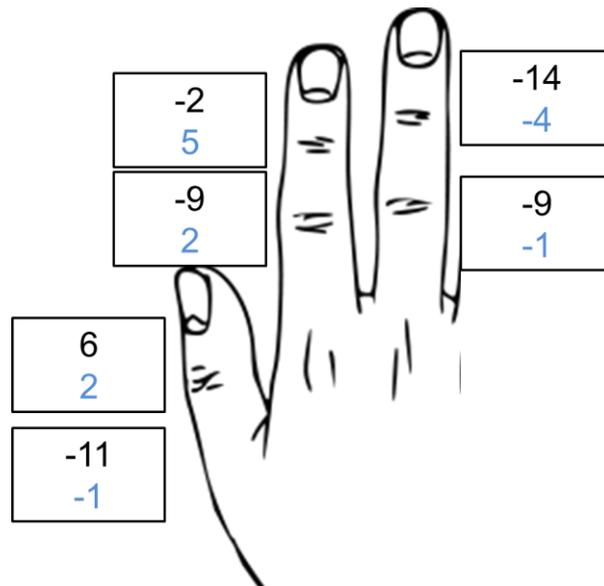**Figure 71: Difference in Flex/Ext (black) and Abd/Add (blue) for the bottle task**

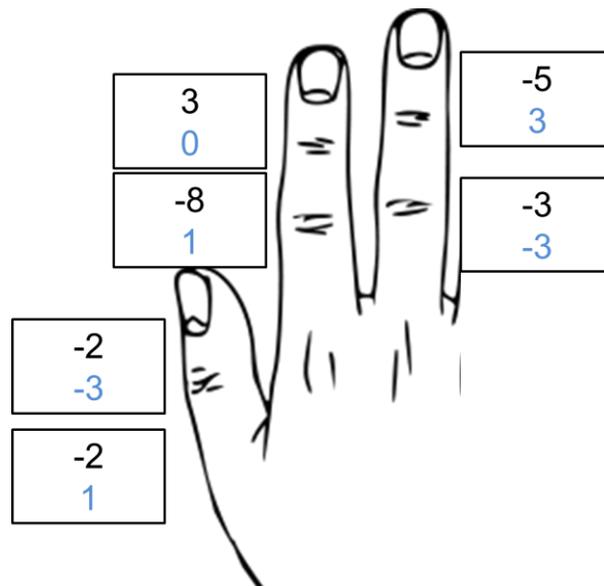**Figure 72: Difference in Flex/Ext (black) and Abd/Add (blue) for the tap task**

Figure 73: Difference in Flex/Ext (black) and Abd/Add (blue) for the button task
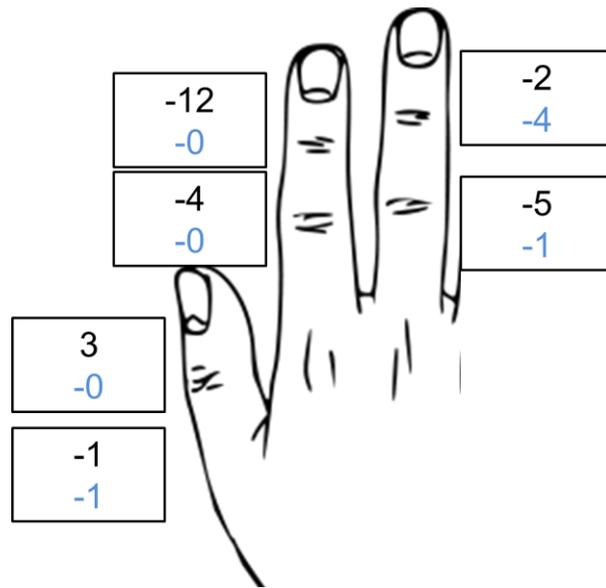
Figure 74: Difference in Flex/Ext (black) and Abd/Add (blue) for the sentence task

Curriculum Vitae

Ahmed Tanashi

Education

Master of Engineering Science, Biomedical Engineering   Sept 2017-Present
Western University
>   Thesis: Evaluation of Finger Kinematics for Analysis of Joint Protection Programs
>   Supervisor: Dr. Emily Lalone

Bachelor of Mechanical Engineering with Professional Internship   Sept 2012-Apr 2017
Western University
- Dean's Honor List: 2013, 2014, 2015, and 2017
- Graduated Spring 2017 with distinction

Practical Elements of Mechanical Engineering College Certificate   May-Aug 2014
Fanshawe College

Research Experience

Graduate Research Assistant, *Musculoskeletal Biomechanics Laboratory* May 2017-Present
Western University, London, Ontario

Research Assistant   May-Aug 2016
Robarts Research Institute, London, Ontario

Conferences and Publications

London Health Research Day (LHRD) 2019   May 2019
London, ON
Evaluation of Finger Kinematics to Measure Hand Function During Grip
Poster Presentation
Authors: Ahmed Tanashi, Dr. Louis Ferreira, Dr. Emily Lalone

Ontario Biomechanics Conference   March 2019
Victoria, BC
Evaluation of Finger Kinematics to Measure Hand Function During Grip
Poster Presentation
Authors: Ahmed Tanashi, Dr. Louis Ferreira, Dr. Emily Lalone

Canadian Orthopaedic Research Society Annual Meeting   June 2018
Victoria, BC
Evaluation of Finger Kinematics to Measure Hand Function During Grip
Poster Presentation
Authors: Ahmed Tanashi, Dr. Louis Ferreira, Dr. Emily Lalone

Canadian Bone and Joint Conference   May 2018
London, ON
Evaluation of Finger Kinematics to Measure Hand Function During Grip
Poster Presentation
Authors: Ahmed Tanashi, Dr. Louis Ferreira, Dr. Emily Lalone

London Health Research Day (LHRD) 2018   May 2018
London, ON
Evaluation of Finger Kinematics to Measure Hand Function During Grip
Poster Presentation
Authors: Ahmed Tanashi, Dr. Louis Ferreira, Dr. Emily Lalone

Teaching Experience

Graduate Teaching Assistant, *Western University*   Jan-Apr 2019
    Materials Science, Dr. Hamidreza Abdolvand

Graduate Teaching Assistant, *Western University*   Sept-Dec 2018
    Advanced Topics in Computer Aided Design, Dr. Pawel Kurowski

Graduate Teaching Assistant, *Western University*   Jan-Apr 2018
    Advanced CAE: Reverse Engineering, Dr. O.R. Tutunea-Fatan

Graduate Teaching Assistant, *Western University*   Sept-Dec 2017
    Mechanics of Materials, Dr. Emily Lalone

Work Experience

Engineering Intern   May 2015-Apr 2016
McCormick Canada, London, Ontario

Awards and Scholarships

CMHR Transdisciplinary Bone & Joint Training Award
Received in September 2018 for a duration of 3 terms

Ontario Graduate Scholarship
Received in September 2018 for a duration of 3 terms

Western Graduate Research Scholarship

Western Engineering Competition
1st Place Group in Senior Design 2016
1st Place Group in Senior Design 2017

McCormick International Scholarship
Received in 2013 and renewed in 2014, 2015, and 2017

IDeA Competition
2014 IDEA of the year – top finalist
    Phineas Sensor System