5-9-2019 10:00 AM

Investigating Grip Range of Motion and Force Exerted by Individuals with and without Hand Arthritis during Functional Tasks and while Swinging a Golf Club

Sara Frances Holland
The University of Western Ontario

Supervisor
Lalone, Emily
University of Western Ontario; Roth McFarlane Hand and Upper Limb Centre (HULC), St. Joseph's Healthcare Centre Co-Supervisor
Ferreira, Louis
University of Western Ontario; Roth McFarlane Hand and Upper Limb Centre (HULC), St. Joseph's Healthcare Centre

Graduate Program in Mechanical and Materials Engineering
A thesis submitted in partial fulfillment of the requirements for the degree in Master of Engineering Science

Recommended Citation

Holland, Sara Frances, "Investigating Grip Range of Motion and Force Exerted by Individuals with and without Hand Arthritis during Functional Tasks and while Swinging a Golf Club" (2019). *Electronic Thesis and Dissertation Repository*. 6214.
https://ir.lib.uwo.ca/etd/6214

Abstract

Hand arthritis is the leading cause of disability in individuals over the age of 50; resulting in dysfunction and pain, making activities of daily living and recreational activities such as golf difficult. Few studies have been conducted on the biomechanical response of individuals with hand arthritis when performing functional activities. This research quantified hand grip movements and strength differences seen in individuals with hand arthritis. Using a video-based motion capture system (Dartfish), a grip limitation of 17.2% (maximum flexion), and 12.7% (maximum extension) was discovered. A wireless finger force measurement system (FingerTPS), was used to show that larger diameter, softer firmness golf grips assisted in reducing the grip force in individuals with and without hand arthritis during a golf swing. This research will benefit the sport biomechanics and clinical fields, providing quantitative results to develop more sophisticated joint protection devices and gain a better understanding of hand arthritis mechanics.

Keywords

Activities of daily living (ADL), Dartfish, FingerTPS, golf grips, hand arthritis, golf grip force.

Co-Authorship Statement

Chapter 1: Sara Holland – wrote manuscript

Emily Lalone – reviewed manuscript

Chapter 2: Sara Holland – data collection, statistical analysis, wrote manuscript

Emily Lalone – study design, statistical analysis, reviewed manuscript

Joy MacDermid – statistical analysis review, reviewed manuscript

Kathryn Sinden – assisted in the study design

Louis Ferreira – reviewed manuscript

Jim Dickey – reviewed manuscript

Timothy Burkhart – assisted in the statistical analysis

Ahmed Tanashi – assisted in data collection

Lauren Straatman – assisted in data collection

Chapter 3: Sara Holland – study design, data collection, statistical analysis, wrote manuscript

Emily Lalone – study design, statistical analysis, reviewed manuscript

Joy MacDermid – statistical analysis review, reviewed manuscript

Timothy Burkhart – assisted in the statistical analysis

Baraa Daher – assisted in the data analysis and collection

Amelia Carver – assisted in the data analysis and collection

Ahmed Tanashi – assisted in data collection

Chapter 4: Sara Holland – wrote manuscript

Emily Lalone – reviewed manuscript

Acknowledgments

I would like to acknowledge and thank those who assisted me throughout this project. Firstly, a tremendous thanks to Dr. Jim Dickey for allowing me to use your Biomechanics Laboratory for my testing and for always finding time to assist me with various components of my project. I would also like to thank Dr. Joy MacDermid for funding the purchase of the FingerTPS sensor system. I am very grateful for your guidance on the statistical approaches needed for my study, and for your insight into the clinical side of the biomechanics field. A huge thanks to Paul Sheller and Stephen Mallinson of the Western Engineering Finance and Stores (EFS), for dealing with all of my warranty returns, travel issues, and for participating in my study. Thank you to my co-supervisor Dr. Louis Ferreira, for expanding my academic knowledge throughout my time at Western. I appreciate the time that you spent advising me on troubleshooting techniques and on the structure of my study protocol.

To Marc Elliott and Marc Webster – you two were extremely helpful throughout this entire process, running trial tests, being there to bounce ideas off of, recruiting participants, and participating in my study yourselves. I also want to thank you for connecting me with Martin Neil, the Ping representative at Sunningdale Golf and Country Club, who supplied me with the golf clubs used in my project.

Most importantly I would like to thank my supervisor Dr. Emily Lalone. I cannot begin to express the gratitude and respect that I have for you, and the mentorship that you provided me over the course of this project. You gave me the opportunity to combine my passion for golf with my engineering background and I cannot thank you enough!

Thank you to the members of the Human Biomechanics Laboratory: Ahmed, Madeline, Michael, Andrea, and Puneet. Special thanks to Ahmed Tanashi for helping me during testing, conducting study statistics, and for being such a great person to work alongside. Thank you to all the students who helped keep this project moving smoothly: Lauren, Sydney, Baraa, Amelia and Kevin. I would also like to thank all of my friends, specifically my best friend Michaela Khan of the Wolf Orthopedic Biomechanics Laboratory at Western, for keeping me sane and supporting me in so many ways throughout the last few years.

Lastly, I'd like to thank my parents, Scott and Shirley Holland, who always support and encourage me to do my best and to never stop trying, even when things get tough or do not work out. I would not be the person I am today without you!

Table of Contents

List of Tables

List of Figures

Symbols and Acronyms

°	Degree(s)
X_E	Baseline maximum extension (grip configuration equation)
X_F	Baseline maximum flexion (grip configuration equation)
γ	Conversion factor (grip configuration equation)
%	Percentage
3D	Three-dimensional
2D	Two-dimensional
ADL	Activities of daily living
ANOVA	Analysis of variance
CI	Confidence interval
CMC	Carpometacarpal
DIP	Distal interphalangeal
DOF	Degrees of freedom
EM	Electromagnetic tracking
IP	Interphalangeal
JPP	Joint protection program
MCP	Metacarpophalangeal
mm	Millimeter(s)
MRI	Medical response imaging
N	Newtons
OA	Osteoarthritis
P	Significance accepted when $P<0.05$
PIP	Proximal interphalangeal
RA	Rheumatoid arthritis
ROM	Range of Motion
s	Seconds
SD	Standard deviation

Chapter 1 – Introduction

1 Overview

One can argue that the hands execute the most important kinematic functions of the body. They mold, shape, and grasp various objects with either stability and strength, or delicate precision. The hands are responsible for performing many of the activities that are executed daily. This results in the joints being constantly under stress which can lead to injuries and diseases. The most common joint disease is arthritis. One of the most prevalent locations for arthritis to occur is in the hands. Hand arthritis, specifically osteoarthritis (OA), causes difficulties in range of motion (ROM) and grip strength, which greatly limits one's ability to perform various activities of daily living (ADL). Hand arthritis also makes it challenging to live an active lifestyle through the participation in recreational activities such as golf. Through understanding the biomechanics of the hand, an appreciation of the importance of one's grip can be gained. This chapter provides an overview of hand anatomy, ROM, grip strength, and hand arthritis. Key background information on the game of golf, the equipment (specifically the grips), and gripping styles will be highlighted. Finally, various measurement techniques and tools for assessing joint motion and grip strength forces will be presented.

1.1 Anatomy

1.1.1 Distal Upper Extremity

1.1.1.1 Distal Upper Extremity Bone and Joint Structures

The upper limb is an extension of the torso, linked through a kinematic chain comprised of the shoulder, elbow, wrist, and hand. The wrist consists of eight carpal bones having four degrees of freedom (DOF) being flexion/extension, supination/pronation, radial/ulnar deviation, and circumduction [1]. The wrist complex connects the distal aspects of the radius and ulna of the forearm to the hand. Controlled by muscles in the forearm, the hand is able to mold and grasp different objects to accomplish various tasks. The hand consists of 19 bones, 15 articulations, and 19 muscles [2]. Of these 19 bones, there are five metacarpals, five proximal phalanges, four intermediate phalanges, and five distal phalanges (Figure 1) [1]. Each of the long finger segments consist of three joint meeting points being condyloid structures: metacarpophalangeal (MCP), proximal interphalangeal (PIP), and distal interphalangeal (DIP) (Figure 2) [3]. The long finger segments each have four DOF. The DIP and PIP joints each have one DOF being flexion/extension, where the MCP joints have two DOF of radial/ulnar deviation (Figure 3a), and flexion/extension (Figure 3b) [4]. The thumb is unique as it has two joints being the interphalangeal (IP) and MCP joint which are condyloid structures having one DOF (Figure 4a) [3, 5]. The joint types that connect the proximal aspect of the metacarpals of the finger segments, and thumb to the wrist complex are the carpometacarpal (CMC), and basal CMC joint, respectively. For the long finger segments, the CMC joints have only one DOF. The basal CMC of the thumb is of convex structure with three DOF being flexion/extension, radial/ulnar deviation, and circumduction (Figure 4b).

Each of these joint types, though different in physical structure, have a similar encapsulated features in that they are synovial joints (Appendix A). Synovial joints join the meeting ends of two bones with a fibrous joint capsule creating a highly vascular and active cavity [5]. Each end of the bones have a layer of cartilage acting as cushions between the meeting points of the bones [5]. With these components and the joint cavity containing a lubricant known as synovial fluid, it allows the bones to easy slide into their respective ROM [5].

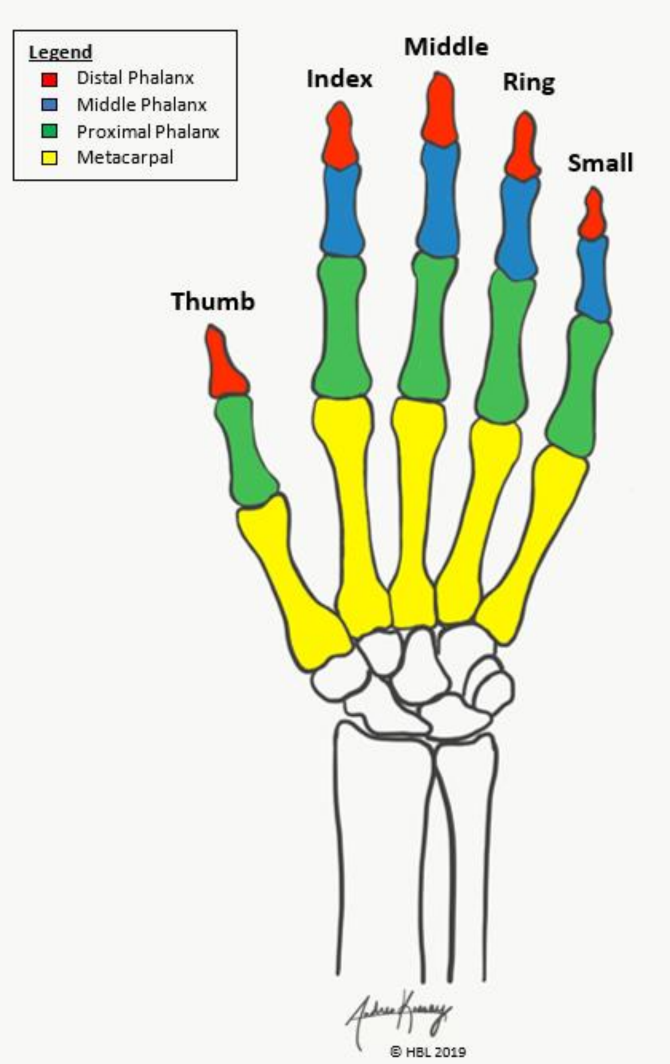


Figure 1: Exhibiting the 19 hand bone locations of the distal phalanx, middle phalanx, proximal phalanx, and metacarpal bones.

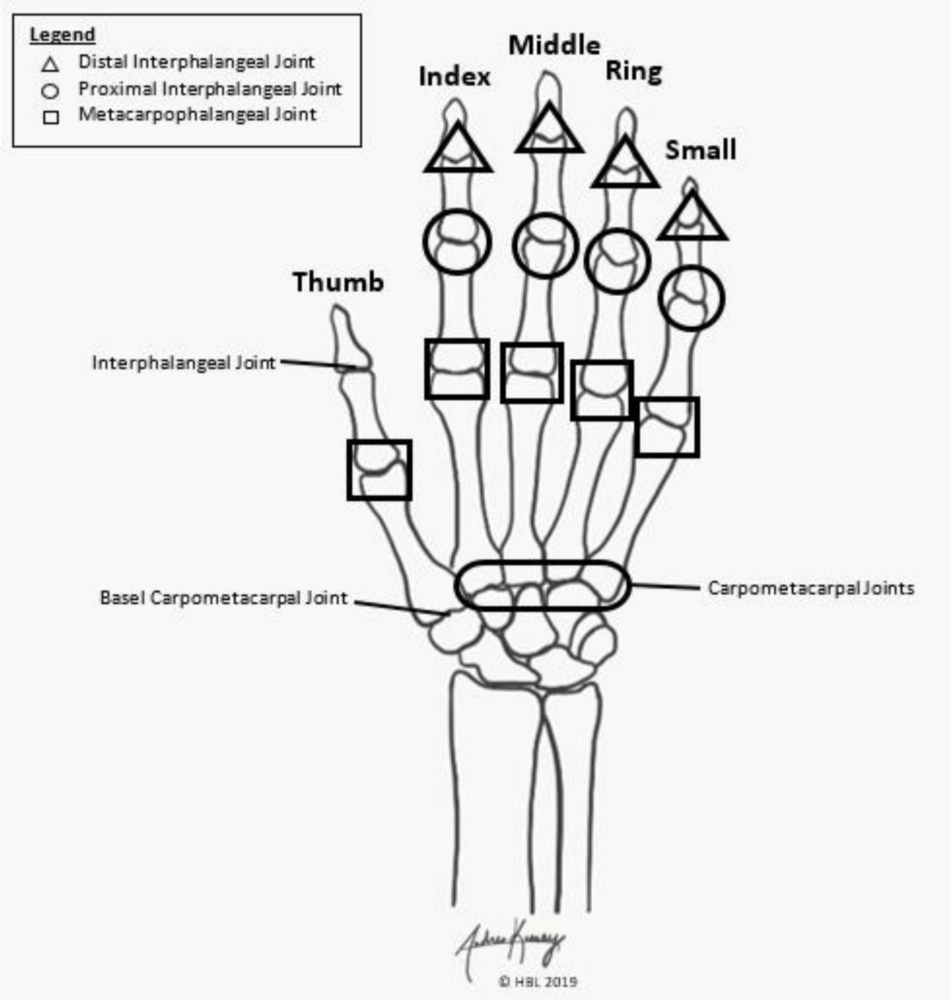


Figure 2: Joint locations of the hand with the distal interphalangeal (DIP), proximal interphalangeal (PIP), metacarpophalangeal (MCP), and carpometacarpal (CMC) joints of the finger segments and the interphalangeal (IP), MCP, and basal CMC of the thumb identified.

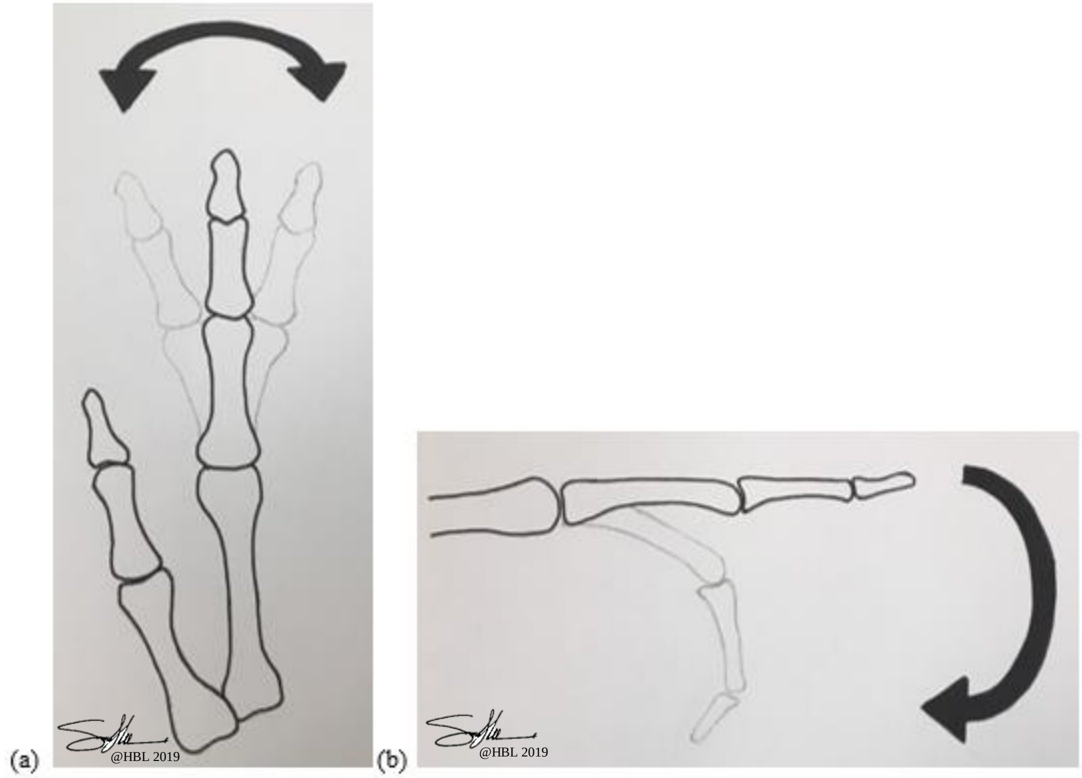


Figure 3: Long finger segments range of motion capabilities of (a) the MCP joint for radial and ulnar deviation, and (b) the DIP, PIP, and MCP joints for flexion/extension (lateral view).

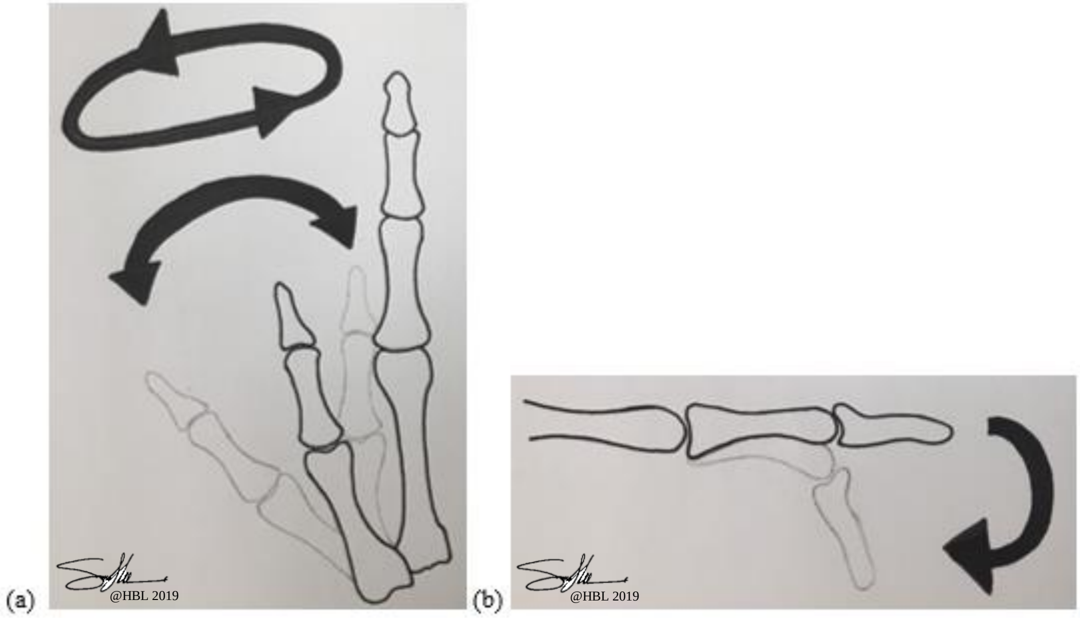


Figure 4: The thumb segment range of motion capabilities of (a) the basal CMC joint for flexion/extension, radial/ulnar deviation, and circumduction, and (b) the IP and MCP joints for flexion/extension (lateral view).

1.1.1.2 Distal Upper Extremity Muscles and Tendons

The intricate movements of the hand require the use of multiple muscles to maneuver each joint of the hand through its respective ranges of motion. One of the major muscles responsible for these movements is the flexor digitorum profundus. This is a deep forearm muscle which extends out into four tendons that connect into the tips of the index, middle, ring, and small finger [3]. The flexor digitorum profundus gives the fingers their sequential strength capabilities, particularly during grasping tasks involving long circular objects such as a hammer, tennis racquet, baseball bat, or golf club handle. Unlike the long finger segments, the thumb uses multiple individual muscles to perform various grasping and pinching actions. The extensor pollicis brevis, and flexor pollicis longus are located on the dorsal side of the forearm and extend into the base of the proximal phalanx [3]. These muscles assist in moving the IP and MCP joints through flexion and extension [3]. The adductor pollicis provides power for pinching tasks, and the abductor pollicis longus abducts the thumb away from the long finger segments [3]. These muscles move the basal CMC joint of the thumb through radial/ulnar deviation and circumduction (Figure 5).

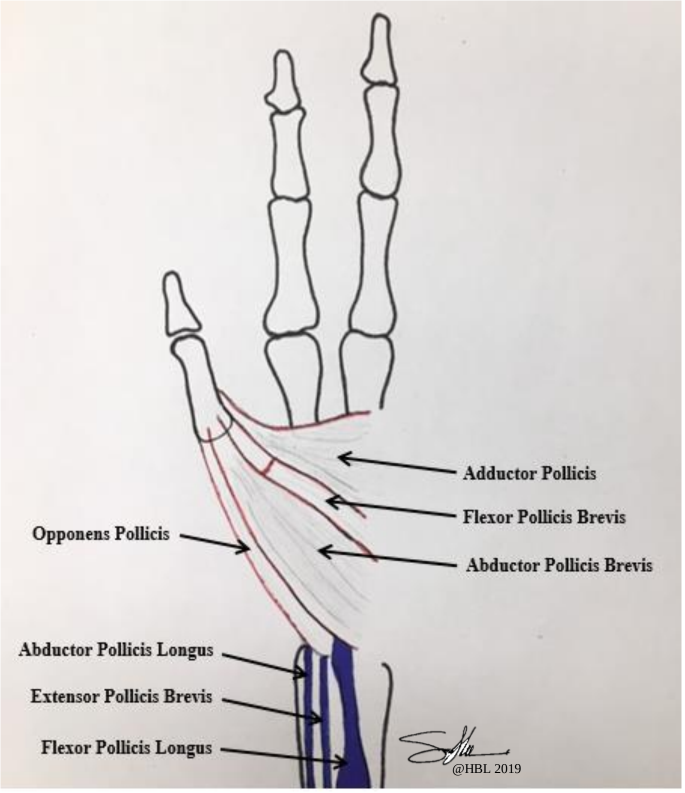


Figure 5: Muscles of the hand which move the thumb through its respective ranges of motion.

1.1.2 Biomechanics of the Hand and Wrist

As discussed above, multiple joint structures are present within the hand and wrist to allow for various movements. With tendons in the hand being extensions of muscles in the forearm, there is a unity between the fingers and wrist. This gives explanation to the restricted movements of either the wrist or finger segments when particular actions are performed. These biomechanical constraints predominantly relate to the connective tissues and muscle fiber lengths in the hand, wrist, and forearm. A muscle is made up of multiple, long cylindrical fiber chains called filaments, consisting of smaller subunits called sarcomeres [6]. Sarcomeres are arranged end to end and contain two types of contractile proteins, actin, and myosin. Actin protein myofilaments (thinner of the two) slide along the myosin protein myofilaments (thicker of the two) to extend and contract the respective muscle [6]. The muscle fiber length dominates the full movement potential in which a joint can maneuver through. The muscles and tendons in the forearm that cross over the wrist to connect into the hand, do not have the physical length to allow for full ROM in multiple joints simultaneously. Oatis *et al.* identified these occurrences by demonstrating that when the fingers move into full flexion (a fist), the wrist naturally moves into a slightly extended position [7]. This reaction gives extra length in the tendons to allow the finger segments to fully flex. This occurrence is not only seen in the hand and wrist network, but in other locations of the body where tendons cross over multiple joints. Textbooks by Hamill and Knutzen *et al.,* [8], and Nordin and Frankel *et al.,* [9], have investigated this topic. However, they fail to inspect the ROM capabilities of a single joint when another is in a certain position, such as the individual finger joints ROM when the wrist is in flexion or extension. These concepts have however been investigated in terms of the hands' grip strength capabilities when the wrist is in various positions. Plewa *et al.* demonstrated that ulnar deviation torques were highest in a neutral wrist position [10]. For other wrist positions (combinations of flexion/extension, radial/ulnar deviation, and pronation/supination) the torques were highest when the wrist was not in a neutral position. Understanding these basic kinematic capabilities of the hand and wrist, provides insight into the operation of the hand's multiple gripping patterns.

Throughout the course of a day, a person can go through over 4000 different gripping positions [11]. This illustrates the human hand's unique versatility, and its crucial function in conducting everyday activities. The two common grip categorizations are the precision and power grip. Variations of these grips are used for activities conducted on a daily basis. The precision, or pinch grip, refers to the small, controllable gripping patterns, using the thumb, and distal palmar section of the long fingers. The precision grip can be broken down into different styles being the tip-to-tip, pulp-to-pulp, lateral pinch, and the chuck pinch [12]. The power grip typically uses the fingers and palm, placing the hand in a fist position, where the fingers are typically in flexion [12]. Recruiting multiple flexor muscles to generate a large grip force is commonly used for grasping large, heavy objects such as a hammer, or carrying a grocery bag. The choice between a precision or power gripping style is dominantly influenced by the shape and size of the object, rather than the task being performed [12]. However, the current literature only provides a cursory understanding into the complexity of the kinematic motion of the fingers and has only evaluated a limited number of activities of daily living (ADL). With the two main indispensable functions of the hand being ROM and grip strength, these components need to be fully understood in order to gauge how different ADL should be performed or adapted.

1.1.3 Grip Range of Motion

The ROM capabilities of the hand allow it to mold and shape objects in order to perform different tasks. A joint motion and functional assessment book written by Clarkson *et al.*, presented the maximum ROM of the joints in the long finger segments (MCP: 0-90°, PIP: 0-100°, DIP: 0-90°) and thumb (CMC: 0-15°, MCP: 0-50° and IP: 0-80°) [13]. These multiple ROM capabilities are performed within a small space. This makes evaluating the dynamic movements of the hand difficult. In previous research, gripping ROM evaluations have been limited to using only standard cylindrical objects. Through affixing pressure-sensitive sheets to a cylindrical tube, measurements of both grip ROM and strength have been evaluated [14], [15]. Instrumented gloves have also been used to measure finger joint ROM and grip force when grasping cylindrical objects [16]. Results demonstrated that grip strength was more affected by the MCP joint flexion angles than PIP joint flexion angles. However, with these systems being bulky, ridged, and having low accuracy, it undermines the reliability of the results. Other, more advanced techniques to measuring grip ROM have been used such as optoelectronic motion analysis system, and digital photographic imagery. A three-dimensional (3D) quantitative and objective method based measurement technique [15], and reconstructed 3D locations of markers drawn on the skin [17], have been established and utilized. Though more sophisticated, implementing these large complex systems to measure the small joints of the hand, still pose issues of accuracy and the ability to appropriately capture natural movements. The full flexion and extension capabilities of the hand can be seen below in Figure 6.

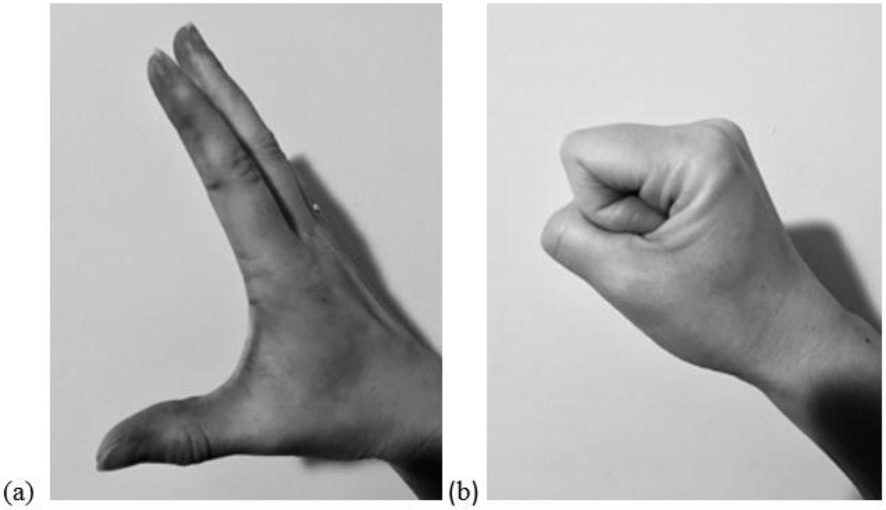


Figure 6: Range of motion (ROM) capabilities of the hand demonstrating (a) maximum extension, and (b) maximum flexion.

1.1.4 Grip Strength

A person's grip strength capability, varies depending on numerous factors: age, sex, range of motion, and muscle size and length [18]. Mathiowetz *et al.* evaluated 628 volunteers (310 men, 318 women) aged 20 to 94 years of age, conducting four hand strength measures: tip pinch, key pinch, palmar pinch, and grip strength [19]. It was found that the mean grip strength for both male, and female participants is 439.0 Newtons (N) and 259.5 N, respectively [19]. It was also discovered that grip force varied between the different gripping patterns of pinch and power grip. The pinch grip was found to only exert roughly one quarter of the full power grip force in both sex groups. This difference in grip force would be due to each grip relying on different muscle groups. The angles in which the joints are placed in, determines which muscles are recruited and the magnitude of force which can be generated. The distribution of force across each finger segment is also influenced by the gripping position, and the shape and size of an object. This was demonstrated by Takano *et al.*, who discovered that when grasping cylindrical objects smaller than 30mm in diameter, the thumb generated smaller forces than other fingers, whereas cylinders greater than 50mm, the thumb produced larger forces [20]. As different shaped objects place the hand in distinct orientations, these findings demonstrate the influence that the shape of an object has on the finger forces generated.

The complexity in the ROM and grip strength functions of the hand, shows their contributions to the ability of the hand to perform various precision and power operations. Abnormalities and diseases of the hand can greatly influence these functions. Hand arthritis, specifically osteoarthritis, is a disease which causes difficulties in both ROM and grip strength causing dysfunction and pain.

1.2 Hand Arthritis

Arthritis is the number one cause of disability in Canada, affecting 1 in 5 individuals over the age of 15 [21]. It is an incurable disease that causes dysfunction and pain making daily activities difficult. The most common forms of arthritis are osteoarthritis (OA), rheumatoid arthritis (RA), and psoriatic arthritis [22]. All of these forms of arthritis cause inflammation and joint instability. Differences arise in their initial triggers, and stages of disease progression. Rheumatoid arthritis (RA) is an autoimmune disease where the immune system attacks the joint structure. Psoriatic arthritis initially begins as a skin condition and progresses to joint inflammation causing pain, stiffness, and swelling [22]. Osteoarthritis is the most prevalent form of arthritis, more frequently occurring in women, and is predominantly induced by overuse and aging. Osteoarthritis affects synovial joints promoting inflammation, swelling, cartilage break down, nerve damage, and in severe cases bone-on-bone contact [23]. In the early stages of OA, inflammation causes enlargement of the synovial joint cavity. Over time this stretches and weakens the surrounding ligaments, prompting malalignment and improper movement of the joint [24]. Locations in the body most commonly affected by OA are of the hands, and weight bearing joints such as the hips and knees. Of the hand, the DIP, PIP, and the base of the thumb (CMC) are most frequently affected [25].

Primarily, osteoarthritis is clinically diagnosed by a physician through physical examination. Key characteristics identified are swelling in three or more joints, pain, and morning stiffness [23]. Imaging techniques and lab tests allow physicians to verify, or contradict their physical assessments, as they provide a visual representation of the individual's internal joint structure. Devices such as x-rays and magnetic response imaging (MRI) are used to observe joint space narrowing, or the specific cartilage structure [26]. Joint fluid analysis tests can also be used to assess if there is an increase of the cell count in the joint cavity which indicates inflammation [26]. Tehranzadeh *et al.* compared MR enhanced, and non-enhanced imaging techniques to evaluate tenosynovitis of the hand and wrist on patients with inflammatory arthritis and tenosynovitis [27]. It was found that contrast-enhanced images allowed for early detection of tenosynovitis in acute and subacute stages [27]. This technique allows for early treatment and possible prevention of the disease developing into different forms of arthritis [27].

1.2.1 Hand Arthritis in Relation to Grip Strength and Range of Motion

As stated above, the hands' grip strength and ROM capabilities, give the hand its unique versatility. Hand arthritis, specifically OA, causes frailty of these functions due to the breakdown of the synovial joints. Zhang *et al.* demonstrated that OA leads to a 10% reduction in maximal grip strength [25]. However minute this difference may seem to an individual with healthy hand function, it can have a large impact on one's quality of life. This level of impairment limits one's natural ability to tightly grasp objects such as when carrying bundles, hand writing, and handling small objects [25]. Individuals with hand arthritis also exhibit difficulties in situations such as pushing one's body mass upward against gravity when standing from a chair [25]. Assistive devices and joint protection programs (JPP) have been put into place to assist individuals with hand arthritis to continue to perform daily activities with as little pain as possible.

1.2.2 Joint Protection Programs

Joint protection programs (JPP) are self-management strategies to protect the joints and maintain function. They consist of adaptations of common household items and adjustments to how daily activities are performed. Depending on the cause of arthritis, JPP can help individuals preserve the function of their joints, maintain joint alignment, and slow the progression of arthritis [24]. These programs can also be used by individuals with healthy hand function to minimize the damaging stresses placed on the joints when conducting repeated daily tasks. Kleinert *et al.* wrote a joint protection handbook which illustrates 10 joint protection principles, and offers information about arthritis, exercises to improve quality of life, strategies to minimize flare-ups, and reducing further deformities [24]. Key recommendations for individuals with hand arthritis are to avoid tight pinching and gripping activities (Figure 7), positions that place excessive or constant pressure on joints, and prolonged static positions [24]. If continued strain is applied to already damaged joints, it will cause further deformities and discomfort. It is also recommended that individuals with arthritis perform a variety of daily exercises to increase muscle strength and ROM, to promote healthy synovial joint function [24]. As the synovial lining is permeable, performing daily exercises assists in bringing new cells into the joint capsule and filters out the old cells to maintain proper joint health and articulation. Strengthening activities can include a variation of simple hand flexion and extension movements, lifting small weights, or participating in recreational activities such as golf. This joint protection hand book, though informative, is not evidence based. Having also been published in 1988, it consists of outdated activities of daily living (ADL), such as a rotary phone. This demonstrates the need to provide updated, evidence based strategies, to assist the growing population of individuals with hand arthritis.

Figure 7: Joint protection tools and techniques to avoid positions that foster deformity. The images on the left represent the positions to avoid where the images on the right incorporate joint protection adaptions.

1.3 Joint Motion Analysis

Joint motion tracking has been used to study human body kinematics during different ADL. It has also been used to evaluate the progression of different joint diseases. In 1965, the American Academy of Orthopaedic Surgeons were the first to publish a text for measuring joint ROM [28]. The main point stated was that visual estimations were just as reliable as goniometer measures [28]. This was later disproved by van de Pol *et al.* [29]. From this discovery, various techniques and tools for measuring ROM have made great strides. However, manual and digital goniometers are still the most commonly used method by both researchers and clinicians [30]. Concerns of human error in reading measurements, repeatability in identifying consistent joint center locations, and only having the ability to measure static positions, greatly limits their use [31]. To address these concerns, more advanced tracking systems have been developed.

Electromagnetic (EM) tracking uses a magnetic field to digitally track the position and orientation of joints in 3D space [32]. Research has concluded on the effectiveness of EM tracking in cadaveric specimens for elbow joint kinematics [33]. However, in-human trials are lacking. Reasons for this are due to the system being bulky and restrictive, consisting of multiple bundles of wires, and issues concerning skin movement [33]. A technique which addresses these limitations is optical tracking.

Optical tracking tools such as Microsoft Kinect V2 Sensor, Vicon, and Optitrack [34]–[36] utilizes less invasive techniques, to easily capture dynamic human movements. This technique uses video cameras to track the movement of anatomical landmarks for both two-dimensional (2D), and more advanced 3D analyses. Markers allow for easy and consistent identification of the joints being evaluated. The two types of markers used are passive and active. Passive markers reflect infrared light, where active markers emit infrared light [37]. Both types of markers can be either small reflective stickers, or large retroreflective markers [37]. Constant line-of-sight between the markers and camera is necessary to obtain the appropriate measures. Optical tracking has the advantage of being minimally invasive, having high accuracy and resolution, while remaining small, and of low cost [38]. Current literature has demonstrated the accurate tactics of EM and optical tracking of large joint motions (knee, hip, shoulder, and elbow) in 3D space during both recreational and ADL.

As addressed above, the hand consists of multiple small components, operating within a small space. This makes it challenging to track the kinematic movements. Van De Noort *et al.* compared a new 3D PowerGlove containing multiple miniature inertial sensors, with an opto-electronic marker system, during specific finger tasks in three healthy subjects [39]. Angle differences were the largest during fast, and circular pointing tasks [39]. Large amplitude difference of 15.8mm were also shown during a fast finger tapping task [39]. These variabilities between a new 3D measurement system and a more commonly used opto-electronic tracking system, demonstrate the challenges of measuring the kinematics of the hand.

1.4 Grip Force Measurement Systems

Common measurement devices such as load cells, strain gauges, and capacitive sensors, have been used to measure grip force. In the current literature, pressure-sensitive sheets fixed to a cylindrical tube, and instrumented gloves, have been designed and tested [14]–[16]. Each of these techniques have produced similar results. However, each of these studies only quantified forces when grasping cylindrical objects. Fowler and Nicol *et al.*, recognized the limitations in 3D load measurement tools and manufactured a new six-degree-of-freedom force transducer to measure individual finger loads [40]. The device consisted of a strain-gauged tubular section and a cantilever load cell to measure both shear and bending moments, to a high degree of sensitivity and accuracy [40]. Fowler and Nicol *et al*. incorporated this six-degree-of-freedom force transducer into several ‘opening’ and ‘closing’ household objects such as a jar, a tap, a key in a lock, and a jug kettle [41]. Twelve healthy volunteers exhibited large external forces of up to 25N and moments up to 1.8 Nm, applied to their index PIP and DIP joints [41]. This technique enabled for more accurate measures than what had been previously presented, and provided input for a full 3D model of the PIP joint [41]. This information could potentially improve surgical techniques for patients with hand arthritis, by establishing a more realistic representation of the loading properties that occur at the interphalangeal joints of the hand [41]. It could also benefit occupational therapists in their understanding of how household tools are used from a detailed biomechanics standpoint.

Advancements in software and hardware systems have allowed for the development of new technologies to measure a variety of gripping tasks. Wearable multifunctional sensors have been developed by Yao and Zhu *et al*. being stretchable conductors made of screen printed silver nanowires [42]. They can detect strain, pressure up to approximately 1.2 MPa, and finger touch having a fast response time of approximately 40 ms [42]. These printed wearable silver nanowire sensors have been used for monitoring thumb movement, motions such as walking, running and jumping, as well as sensing the strain of the knee joint in patellar reflex [42]. The Kato Tech HapLog sensor is another wearable senor which detects the deformation of the finger pad through measuring the horizontal displacement forces experienced at the fingertip when a linear force is applied [43]. This technique does not come in contact with the fingertip pad therefore limiting the interference between the hand/grip interface. Each of these newly developed sensor systems are compact and wireless, allowing for a wide range of activities to be easily analysed. In analysing various ADL, the biomechanics of the hand can be better understood.

1.5 Golf Background

The game of golf was first established in Scotland back in 1457 [44]. A driver, woods, hybrids, irons, wedges, and a putter, make up the 14 club allowance in a player’s bag. On a standard championship course with par of 72 (the number of strokes taken for 18 holes played), on average, a 0 handicap player (a professional player) will hit roughly 14 tee shots with a driver, 22 iron or wedge shots, and 36 putts. This means that roughly 31% of the shots taken during a round of golf are with irons. Unlike the driver, woods, or hybrids, irons are designed with shorter, steel alloy shafts and smaller heads made of solid iron or steel [45]. In the early years, golf clubs were designed from tough woods, such as beech, holly, persimmon, pear, apple, and hickory [46]. In using these materials, club breakage was extremely common, resulting in players having to constantly replace them [46]. This led to the game being associated with the upper class due to the cost of replacing clubs. To better accommodate for a larger percentage of the population, stronger, more durable materials were implemented. Today, clubs are designed using high strength, light weight metals, including titanium, stainless steel, aluminum, carbon graphite, and carbon steel [47]. These advancements in materials and manufacturing techniques, paired with the strides made in the biomechanical analysis of the golf swing, have shaped equipment designs to positively impact each player’s performance. This section will summarize the basics of the game of golf, with common terminology defined. Golf grips and gripping styles will be evaluated, with the biomechanics of the swing highlighted.

1.5.1 Golf Terminology

In 2014, the National Golf Foundation (NGF) reported that nearly 25 million people in the world played the game of golf [48]. Individuals over 50 years of age make up 35% of this population [48]. Golf is played on an 18 hole course, with the basic goal of completing each hole in as few strokes/shots as possible. A handicap or average scoring range is used to gauge player’s skill level. According to Golf Canada, a Handicap Factor is a service mark, that indicates the measurement of a player’s potential ability on a course of standard playing difficulty [49]. In the United States, the average handicap of male and female golfers is 16.1 and 28.9, respectively [50].

1.5.2 Golf Biomechanics

The golf swing is one of the most complex biomechanical movements in sport. It generates large amounts of power, while maintaining stability [51]. The golf swing can be broken down into three main phases: the backswing, downswing, and follow through (Figure 8) [52]. The start of the swing begins with the player in an athletic "ready position", with the club face at address (behind the golf ball). When the player begins to pull the club back, several movements happen simultaneously. The shoulders and hips rotate, body weight is transferred to the back leg, and the wrists hinge, all to create a large energy storage [52]. Once the golf club reaches the top of the backswing with the shaft of the club relatively parallel to the ground, the downswing phase begins. The downswing harnesses the built up energy generated from the backswing and transfers it to the club. This is done through the rotation of the shoulders and hips back to their original starting position. The player's body weight is transferred to the front foot which assists in accelerating the club head. The final phase of the golf swing is the follow through. The player rotates their torso to an upright position facing their target with the club wrapping behind their body.

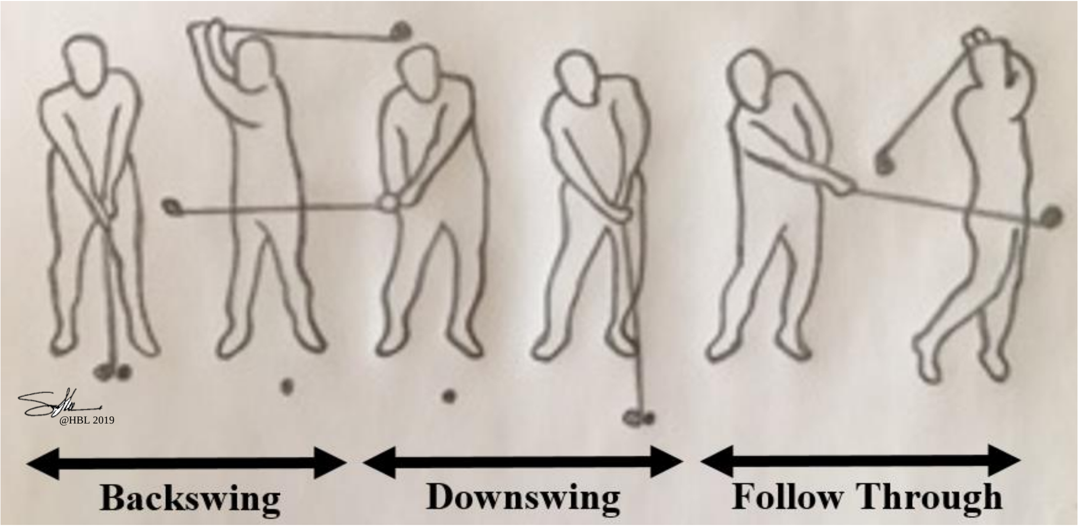


Figure 8: Progression of the golf swing broken down into three phases being the backswing, downswing, and follow through.

1.5.3 Golf Grips and Gloves

Each club is fitted with a grip residing at the end of the club opposite to the head of the club. The two main design components of a golf grip are the material composition and geometry (diameter size). It is unclear when the first golf grips were introduced. However, it is known that they were made of pieces of leather or suede, wrapped around the end of the club [53]. Today, grips are made of synthetic, rubber, or hybrid materials, manufactured into a single piece and slipped over the end of the shaft [53]. For marketing purposes, materials are commonly categorized into soft, medium, and hard firmness [54]. The main goal of these material choices are to provide comfort, sensory feedback, and a high friction coefficient between the hands and grip. In terms of geometry (diameter size), grips are categorized into four sizes: undersized, standard, mid-sized, and jumbo [54]. These categorizations are based on an individual's hand length measures, from the crease of the wrist to the tip of the middle finger.

Often, players feel that the grip alone does not provide enough traction. The common solution to this lack of traction felt is to wear a glove on their top gripping hand (closer to the body). Golf gloves are made from synthetic or leather materials, offering a second skin feel [55]. Since golf is an outdoor sport, players are faced with many different weather conditions. A golf glove provides a better grip on the club in humid or wet conditions, and when a player's hands sweat [55]. FootJoy, who is a notable golf glove manufacturer, estimated that 85% of amateur golfers and 95% of professional tour players, wear a golf glove [56]. This distribution was confirmed by our online survey conducted showing nearly 87% of a sample size of 54 wearing a glove on one or both hands (online survey questions and data shown in Appendix F). The limitations of a glove are that they can restrict the flexion capabilities of a golfer's fingers and thumb, creating excess material bulk. A golf glove's life span is roughly 5 rounds of golf, meaning that they constantly need to be replaced therefore increasing overall cost [55]. They also desensitise the player's grip, not providing the same 'feel' aspect as having direct contact with the grips. However, with golf gloves giving players both comfort and security, they provide a simple solution without having to replace the grips. This club security is especially important for golfers with a weakened grip strength, as a golf glove would provide a higher friction coefficient between the hand/grip interface without needing to increase one's grip force.

Golf companies are beginning to develop custom grips and assistive devices for players with injuries and disabilities. Specially designed gloves and braces are among the tools that have been developed. Also, ‘arthritic’ designed golf grips have been marketed, with designs consisting of a serrated material surface, as well as a soft material oversized design. These tools are designed with the goal of providing more security when swinging the club, while limiting the pain experienced when gripping the club. However, these tools and techniques are not evidence based to quantitatively prove whether their claims are true.

1.5.4 Gripping Styles

When gripping a golf club, the entire palmar side of the hand is utilized with the fingers wrapping around the grip. The top hand (closer to the body) creates a fist position, demonstrating a power grip to provide support when swinging. The precision gripping style is shown by the thumb, index, and middle finger positions of the bottom gripping hand (the hand closer to the head of the club). A palmar pinch orientation allows for the bottom hand to have a lighter grip force to allow for the wrist to easily extend through the back swing. These components are the basis for the three types of golf gripping styles used by players: (1) the interlocking grip, which involves linking the bottom hand small finger with the top hand index finger, (2) the overlapping grip sees the bottom hand small finger lay over top of the top hand index finger, and (3) the baseball grip (ten finger grip). The overlapping gripping style was first popularized by the famous British golfer Harry Vardon in the late 19th/early 20th century [44]. Modifications to this gripping style were made to create the baseball (10 finger) and interlocking gripping style.

1.6 Study Rationale

Hand arthritis, specifically OA, is a common, degenerative disease with no known cure. It affects an individual’s grip ROM and strength capabilities, making it difficult and painful to perform daily tasks. Recreational activities such as golf, where the hands are the only contact point between the play and the club, present further obstacles for individuals with hand arthritis. Research in biomechanics, injury prevention, and safety, have become a focus for many sporting equipment manufacturers. However, the current literature surrounding golf grips and their impact on the hands is lacking. Many of the measurement techniques previously used involve large interferences such as wires, bulky gloves and materials, between the hand/golf grip interface. This interference changes the natural environment of a player's grip. These outdated studies coupled with the advancements in technology and materials, begs the question of which golf grip design is better for individuals with and without hand arthritis in reducing the grip ROM and force when gripping a golf club?

1.7 Objectives and Hypothesis

The overall objective of this thesis was to determine if grip material and geometry can reduce the grip ROM and forces required to appropriately grip a golf club, and to determine whether or not specifically designed golf grips for individuals with hand arthritis can further reduce ROM and finger forces. The specific objectives were:

1. To develop and validate a simple, video-based motion analysis measurement technique, to quantify the hands' grip range of motion (Grip Configuration Model). The Grip Configuration Model will be used to:
    a. Evaluate kinematic changes of the hand
    b. Quantify the grip range of motion differences in individuals with and without hand arthritis during:
        i. Maximum flexion and maximum extension
        ii. Functional tasks involving the hand
        iii. Gripping different golf grip designs
2. To employ a commercially available force measurement system to evaluate the applied individual finger forces, and obtain a total grip force in golfers with and without hand arthritis when swinging a golf club.
3. To detect differences in golfers' total grip force when swinging golf clubs with a variety of standard, and 'arthritic' designed golf grips.

It was hypothesized that:

1. Functional limitations in range of motion in individuals with hand arthritis will be translated to activities of daily living.
2. Larger diameter golf grips will result in a larger golf grip configuration (less flexion in the fingers), where the smaller diameter golf grips will result in smaller (more flexed) grip configurations, in golfers with and without hand arthritis.
3. The larger diameter, softer firmness golf grips will reduce the overall finger forces in both individuals with and without hand arthritis.

1.8 Thesis Overview

In the game of golf, there are three fundamental aspects that work together to create a sound golf grip being grip position, ROM, and grip force [57]. Two of these three fundamental aspects will be explored and tested in this thesis. Chapter 2 will describe a new measurement system known as the Grip Configuration Model. This model evaluates individual grip ROM (grip configuration) when conducting five ADL (Chapter 2), and when gripping various standard and ‘arthritic’ golf grip designs (Chapter 3). The grip force values produced by individuals with and without hand arthritis when swinging each of the different golf grip designs, will be presented in Chapter 3. Finally, Chapter 4 contains an overall conclusion on the results discussed in Chapters 2 and 3, with a summary of future work and significance.

Chapter 2 – The Development and Validation of a Novel Grip Motion Analysis Technique to Evaluate Hand Motion During Activities of Daily Living

2 *Overview*

Obtaining quantitative joint angle measures of the hand is difficult. Motion of the hand involves the complex coordination of numerous rigid bodies with 27 degrees of freedom (DOF). Without having a complete understanding of the kinematics of the hand, the assessment of joint diseases such as arthritis when performing various activities of daily living (ADL) and recreational activities, is not fully understood. This chapter explores currently presented literature on grip ROM in terms of technologies used and their limitations. A cohort of 40 participants (20 healthy participants: 20 participants with hand arthritis, specifically OA) performed maximum flexion/extension of the hand along with five ADL. Using a video-based motion capture system, (Dartfish Movement Analysis Software), the thumb MCP and CMC, and index MCP and PIP joint angles, was measured for each activity. A Grip Configuration Model was established to provide a single percentage value to describe an individual's grip ROM capabilities. This allowed for simple comparisons of the activities performed between the two test groups. Results were compared against the clinically used manual goniometer, and a more advanced electromagnetic (EM) motion tracking system. This chapter presents the results of this study, and provides a discussion and conclusion on the findings.

2.1 Introduction

Arthritis can be costly in both direct illness costs and indirect costs such as those related to work disability as it affects two-thirds of the working population (18-64 years) [58]. One of the most common locations in the body for arthritis to occur is the hands, with osteoarthritis (OA) being the most common form having no known cure [21]. It often leads to substantial pain and disability. In the hand, arthritis is most prevalent in the DIP, PIP, and base of the thumb (CMC) joints, and is more common in women than men [25]. Functional activities that are central to everyday life (recreational, vocational, personal care, hygiene, and domestic) rely on proper hand function. Dollar *et al.* reported that individuals execute 500-625 grasp changes per hour while conducting domestic work in the home [11]. Optimizing the ability to perform these tasks is an important goal for clinicians when treating individuals with musculoskeletal injuries and diseases such as arthritis.

As stated in Chapter 1, individuals with hand arthritis have impairments in their grip strength and ROM. This leads to difficulties when carrying heavy bundles, handwriting, handling small objects, and pushing oneself upwards against gravity from a chair [25]. These challenges can have great impacts on the quality of a person's life. Joint protection programs (JPP) provide adaptive strategies and tools for individuals with reduced ROM and grip strength. They enable individuals to maintain their independence, through the ability of continuing to perform daily tasks [24]. However, many of the tools and techniques are outdated and include strategies that are no longer relevant in today's modern society [24].

Through the use of new motion analysis technologies, a better understanding of the mechanics of how ADL are performed can be quantified. This is central to designing updated and fact driven JPP to optimize hand function. Conducting kinematic analyses of the hand is complex. The hand consists of 19 finger bones, totaling 27 DOF, all working within a small space [59]. Measurement techniques such as goniometry, optical, and EM tracking, have been used to evaluate specific joint motions [32], [60]. As discussed in Chapter 1, these techniques have several advantages, but are not without limitations. Goniometry is the most commonly used but is restricted to static positions, with human error being of major concern [61]. Electromagnetic tracking can measure both position and orientation in three-dimensional (3D) space, however, this technique is restrictive and difficult to mount onto anatomical landmarks and can interact with metal in the testing environment [32]. Conducting *in situ* assessments of the hand, requires the functional tasks to be performed in a relatively small testing space. Chapter 1 also explored several other motion tracking techniques to specifically quantify the kinematic joint motions of the hand. Techniques included optoelectronic motion analysis [15], digital photographic imagery [17], and instrumented gloves [16]. All of these techniques had similar conclusions, demonstrating the correlation between grasp force and finger joint angles when gripping a cylindrical object.

Video or optical tracking analysis systems, are an alternative option for tracking the small joint motions of the hand. This technique is less invasive and can readily be used for numerous functional tasks. One such video tracking system is the Microsoft Kinect V2 Sensor. The validity and reliability of this sensor system was compared against a 3D motion capture system (Vicon, Oxford Metrics Ltd., Oxford, UK) using a sample of 10 healthy male university students performing several upper limb motions such as zipping up a jacket, brushing their hair, and lifting a mug [34]. The Kinect V2 system is a vision device used to recognize contour and special positions, as well as the shape and dimensions of different objects [62]. High-level agreements were observed for shoulder and elbow kinetics for the Kinect V2 system which demonstrated good accuracy in measuring shoulder and elbow flexion/extension angles [34]. Another system is the Dartfish Movement Analysis Software. A previous study evaluated the inter-rater reliability of video gait assessments in children with cerebral palsy [63]. The Dartfish software was found to be a more user-friendly tool than 3D gait analysis systems for measuring movement patterns [63]. Being a high-speed video analysis software, it can be used to monitor and evaluate individuals with arthritis treatment progress in a clinical setting or during a performance based task (golfing etc.). However, it does not substitute for more sophisticated 3D tools or offer the same joint kinematic information [63]. Large joints of the body have been frequently evaluated using Dartfish, as they provide a greater surface area and an unobstructed line-of-site. Previously, Dartfish has been used to describe the functional posture of the shoulder during common ADL. Results demonstrated the clinical relevance in both the Dartfish software itself, and the importance of collecting data in this field [64]. These components demonstrate the usability of video tracking analysis and more specifically the Dartfish Movement Analysis Software for evaluating the small dynamic movements of the hand.

In the current literature, little focus has been given to assessing the kinematic movements of the hand during basic ADL and recreational activities such as golf where the hands are heavily relied upon. Without these evaluations, it has limited the opportunity to fully understand the complex motions of the hand. Having this understanding will allow for more sophisticated tools and techniques to be developed and implemented. This will enable individuals with hand arthritis to be able to more easily perform these activities with minimal pain, and potentially protect healthy individuals' joints from developing arthritis. Therefore, the purpose of this Chapter is to develop and validate a simple, video-based motion analysis measurement technique, to quantify the hands' grip range of motion (Grip Configuration Model), to evaluate kinematic changes of the hand (Objective 1a.) in individuals with and without hand arthritis, during maximum flexion and maximum extension (Objective 1b.i.), and five functional tasks (Objectives 1b.ii.). This will enable the variability between the healthy individuals and individuals with hand arthritis to be easily detected.

2.2 Materials and Methods

2.2.1 Participants

Forty (40) participants (20 healthy participants: 20 participants with hand arthritis, specifically OA) were evaluated for this study (study demographic shown in Table 1). Participants with hand arthritis were previously diagnosed with OA by a clinician, prior to study participation. This was not a criteria for participating in the study, but was a commonality between the participants with hand arthritis. Western University's Research Ethics Board approved the study protocol (Appendix G). Each participant provided informed, written consent prior to study participation. The Patient Rated Wrist/Hand Evaluation was used to rate the participants pain and disability in their wrist and hand, as well as functional difficulties when performing various ADL [65]. In this study, a total score below 20 classified participants as having none or minimal pain/disability, a score between 20 and 80 was considered to have a moderate level of pain/disability, and a score above 80 was identified as extreme pain/disability. This allowed for the degree of wrist/hand related musculoskeletal disabilities to be quantified within the two test groups [66]. Participants were excluded if they were under the age of 18, had any prior disabling hand conditions or wrist injuries within the last year, or had any other form of hand arthritis other than OA, e.g. rheumatoid or psoriatic.

Table 1: Demographic information of participants.

	Healthy Participants	Participants with Hand Arthritis
Gender		
Male	11	2
Female	9	18
Age		
18-35	16	0
36-50	1	1
51-65	2	2
65+	1	17
Hand Dominance		
Right	18	20
Left	2	0
Form of Arthritis		
Osteoarthritis	0	20
Rheumatoid Arthritis	0	0
Psoriatic Arthritis	0	0
Patient Rated Wrist/Hand Evaluation (PRWHE)		
No Pain (PRWHE < 20)	19	3
Moderate Pain (20 < PRWHE < 80)	1	15
Extreme Pain (PRWHE > 80)	0	2
Years Arthritis Diagnosis		
1-10	0	12
10+	0	5
Unsure	0	3

2.2.2 Data Collection

2.2.2.1 Activities of Daily Living (ADL)

All participants performed a series of five ADL with their self-selected dominant hand. A previously developed JPP manual by Kutz *et al.* [24], was utilized to assess the ADL that are typically strenuous or painful for people with hand arthritis. The tasks chosen target movements done when cooking, cleaning, personal care, and hygiene. The categorization of precision and power grips, defined in Chapter 1, were also considered when selecting the tasks for this study. This ensured that a range of movement patterns would be analysed. The five ADL evaluated were:

i. Spray bottle squeeze,
ii. Opening a small diameter size water bottle cap,
iii. Opening a medium diameter size medicine container,
iv. Opening a large diameter size twist jar,
v. Key pinch.

Activity v. requires a precision grip, whereas i. requires a power grip. Tasks ii. to iv. represent a range of small to large diameter twist tops (smallest to largest diameter measurements: 3cm, 5cm, and 8.5cm), with the medium size being a medicine container specifically designed for people with hand arthritis. These three tasks require a combination of precision and power grips. Including tasks that demonstrated these two different categories of grips, the variations in joint angles, and movement demands could clearly be analyzed.

2.2.2.2 Equipment Set-Up and Procedure

Two commercially available video cameras were used to capture the joint angle movements in this study: a GoPro Hero 5 Camera, and a Sony HD Handycam HDR-CX405 Camcorder (high definition camera). The GoPro has a resolution of 4K at 30 frames per second (fps) with 12-megapixal images, and the HD camcorder has a resolution of 1920x1080 at 60fps video with 9.2-megapixal images. The cameras were positioned in specific anatomical planes around the testing room to appropriately capture each participant's movements. The Sony HD Camcorder was positioned directly above the center of the table where the participants performed each task (aerial view). The GoPro was positioned in the non-dominant arm plane at a 45-degree angle from the front of the participants (Figure 9). Both cameras were used to ensure that the participants did not have to be instructed to maintain within a single cameras line-of-sight. This allowed for the participants' natural movements to be easily captured. The positions of the cameras were standardized, adjusted depending on an individual's arm dominance and height.

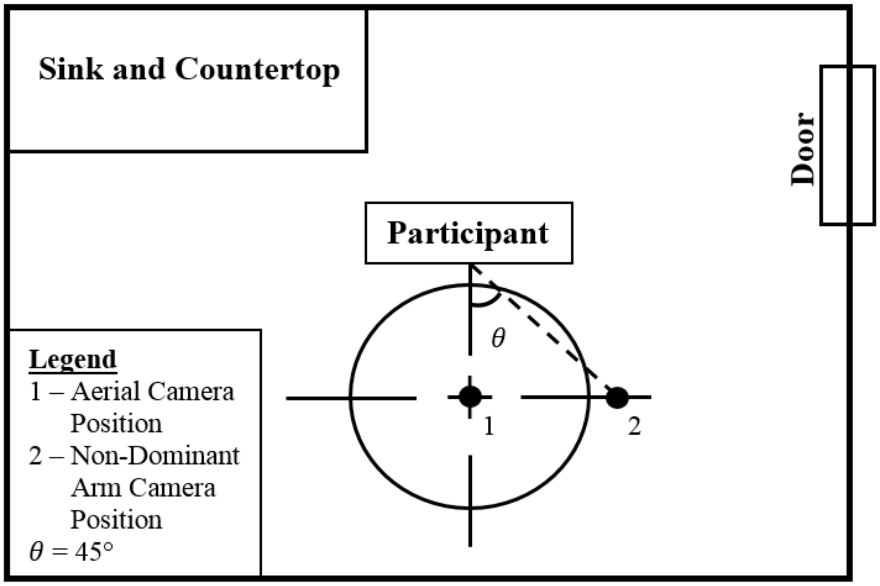


Figure 9: Testing room camera positions set up, shown as a schematic sketch of the room with camera positions for a right hand dominant participant (not scaled to the measurements of the room).

Small 0.6mm removable markers were placed on the anatomical landmarks of participant's dominant hand thumb, index, and middle finger. The purpose of these markers was to maintain visibility of the joint centers throughout the test. This ensured that each joint location could be easily identified when conducting the evaluation in the Dartfish software. Appropriate placement of the markers was essential in the reliability of the grip configuration results. The Bony Palpation Skill Sheet developed by The University of West Alabama Athletic Training and Sports Medicine Center, was used as a common guide for the identification of the anatomical landmarks [67]. It describes the location of the preferred body and joint positions, and provides descriptions of the anatomical locations with images of a skeletal and human model with the particular body or joint position identified [67]. The joints identified in this current study were the metacarpophalangeal (MCP), carpometacarpal (CMC), and the interphalangeal (IP) joints of the thumb; the distal interphalangeal (DIP), proximal interphalangeal (PIP), and MCP joints of the index; and the MCP and PIP joints of the middle finger. The joints identified on the middle finger were solely used as reference points to ensure the differentiation between the index and middle finger during the various activities performed. The raters identified these anatomical landmark locations on the participants by manually articulating the joint of interest and using their fingertips to feel the joint articulation. On the joints of the thumb and index finger, a second set of markers were placed on the ulnar side of the thumb IP joint, and the radial side of the index DIP, PIP, and MCP joints. The joints of the thumb and index finger identified and evaluated, represent the main grasping and pinching finger segments used for nearly every ADL task and recreational activity such as golf. Therefore, in this current study, one's grip ROM for the hand will be defined from the angles created by the thumb and index finger.

The five ADL were performed while wearing finger sleeves over the participant's thumb, index, middle, and ring finger. This was done to maintain consistent marker placement between each participant, and the two evaluators. During the analysis in the Dartfish software, the finger sleeves made it easy to identify out-of-position markers. The wires on the finger sleeves ran along the dorsal side of each finger segment, acting as guides. This allowed for easy manual alteration of the locations of the joint centres to be done within the Dartfish Movement Analysis Software. In evaluating the data, the thumb MCP and CMC, and index MCP and PIP joints, were measured using the angle-tracking tool in the Dartfish Software. The average angles for maximum extension of the four joints, of the healthy participants, with the finger sleeves on and off are shown in Figure 10a and b. The accuracy of marker placement with the finger sleeves on was compared using a paired t-test analysis. This was done to determine if the finger sleeves interfered with the anatomical landmark identification and therefore the joint angle evaluation. Each participant performed two trials of maximum flexion (making a fist) and maximum extensions of the hand with the markers on the finger sleeves, and directly on the participant's skin.

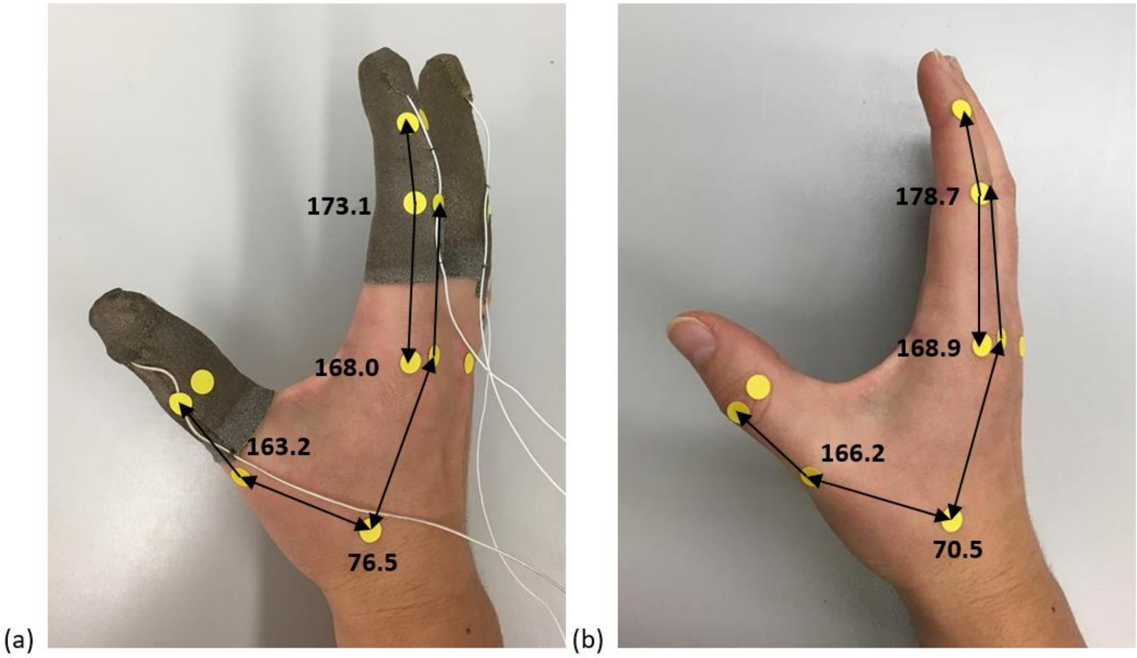


Figure 10: Position and average angle measures of the thumb MCP and CMC and index MCP and PIP joints for the healthy participants (n=20) during maximum extension (a) with the finger sleeves, and (b) without the finger sleeves.

The procedures for performing the five ADL were standardized. This was done by conducting each test using the same lab space, tools, and camera positions. The only instruction provided to the participant was where to stand to ensure visibility of the markers throughout the performance of the activities. The participants were required to perform the five ADL two consecutive times as they normally would in their daily lives. This allowed for natural movements to be captured. The second trial of each activity was evaluated, unless marker visibility was a concern. If the markers in both trials were not visible, the participant's entire data set was excluded from the analysis.

The execution of this procedure and the evaluation of the data explained in the proceeding section was conducted by two evaluators. The steps of the study set-up, anatomical landmark location, and data processing were explicitly followed by each evaluator to ensure there was no variability between or within each evaluator. An intra-rater and inter-rater reliability analysis was also conducted.

2.2.3 Data Processing

The video images from each camera were imported into the Dartfish ProSuite 9.0 video software and edited into short video clips to isolate each task performed. Each video was played separately in the main window of the Dartfish Software to manually track the location of each hand and marker position. In reviewing the videos, one of the evaluators determined which camera orientation gave the best view for the task being performed. Once the camera view was determined, the location of the markers were tracked. When the position of the thumb and index finger were perpendicular to the camera view, the video was paused to obtain a static 2D position of the thumb and index finger of the hand. Identifying when the markers of the thumb and index finger were perpendicular to the camera view was subjective to each evaluator. However, this was controlled based on the standardized camera position.

The hand moves in a three-dimensional (3D) manner, and each activity performed in this current study was conducted in a natural dynamic manner. For the purposes of this current study, we were concerned with 2D planar motions. The dynamic 3D movements of the hand were controlled for as the static images taken for each evaluation represent a static image of the positions the hand moves into when completing these various activities. Also, the grip configuration model is quantifying the flexion and extension 2D movements of the thumb and index finger to represent the grip ROM. Therefore, the abduction/adduction and circumduction movements of the thumb CMC and index MCP were not the main focus for this current study.

Once the appropriate static view was obtained, the angles of the thumb MCP and CMC, and the index MCP and PIP were taken. This was done using the angle-tracking tool in the Dartfish software by placing a vertex on the point of rotation (the joint being measured), and extending the two angle arms out to the markers (joints) on the opposite sides of the vertex. An angle measure was placed on each of the four joint locations and a static image was taken in the Dartfish software. When the angle measures for each activity for a single participant were taken, the images were exported from the Dartfish Software.

2.2.4 Grip Configuration

The Grip Configuration Model is a simple, comparative measurement system, for quantifying individual's grasp capabilities. It was created to evaluate the basic grip ROM of each participant and the tasks performed. The first step was to obtain the angles of the thumb MCP and CMC, and index MCP and PIP joints using the Dartfish software during maximum flexion (making a fist) and maximum extension for all the participants in both test groups. Once each joint angle for all 40 participants was obtained, the joint angles for the thumb MCP and CMC, and index MCP and PIP were averaged for each test group (Table 2).

Table 2: Average maximum extension and average maximum flexion angles (in degrees) for the individuals with and without hand arthritis (n=20 healthy participants: n=20 participants with hand arthritis).

Health Status	**Extension (degrees)**				**Flexion (degrees)**			
	Thumb MCP	Thumb CMC	Index MCP	Index PIP	Thumb MCP	Thumb CMC	Index MCP	Index PIP
Healthy	163.2	76.5	168.0	173.1	141.7	73.3	102.0	67.3
Arthritis	135.9	84.4	155.5	167.8	132.5	81.8	117.0	83.8

The Grip Configuration Model uses the average joint angles of the thumb MCP and CMC, and index MCP and PIP from the cohort of healthy participants (n=20) (see Table 2 above). These values were used as the highest and lowest boundary values to establish an equation to calculate a single percentage value of grip extension of a participant's grip during a specific activity. The joint angle measures from the 20 healthy participants' average maximum flexion angles were used as the base of the equation, being the denominator represented as ($\alpha_{max-flex1-4}$). The numerators of the equation (β_{1-4}) are the joint angle values of the particular activity and participant being evaluated. To first establish the Grip Configuration Model, the healthy average maximum extension values were calculated as a percentage of the maximum flexion values, displayed in the equation below (Equation 1).

$$\left[\frac{\beta_1}{\alpha_{max-flex1}} + \frac{\beta_2}{\alpha_{max-flex2}} + \frac{\beta_3}{\alpha_{max-flex3}} + \frac{\beta_4}{\alpha_{max-flex4}}\right]\left[\frac{100\%}{4}\right] = X_E + 100$$

$$\left[\frac{141.7}{163.2} + \frac{73.5}{76.5} + \frac{102.0}{168.0} + \frac{67.3}{173.1}\right]\left[\frac{100\%}{4}\right] - 100 = X_E \qquad \textbf{(Equation 1)}$$

$$X_E = 60.7\%$$

From $X_E = 60.7\%$, a factor of γ was determined to establish a baseline measure of $X_E =$ 100% maximum extension (Equation 2). The same equation format was used for maximum flexion, resulting in $X_F = 0\%$.

$$\gamma = \left[\frac{1}{X_E}\right][100\%]$$

$$\gamma = 1.65668085996095 \qquad \textbf{(Equation 2)}$$

$$X_E = 60.36\% * 1.65668085996095$$

$$X_E = 100\%$$

Therefore, the healthy average maximum flexion (X_F) angles (a fist position) for each joint were used as the baseline measures, representing the starting or 0% point, to calculate the percentage amount of extension of the hand. The healthy average maximum extension (X_E) angles represent the top limit or 100% point. Values above 50% were considered to be in extension and below in flexion. This is a secondary component of the baseline measurement to assist in distinguishing if positions are in extension or flexion. The healthy participants and participants with hand arthritis maximum flexion/extension, and each of the five ADL performed, were compared to the baseline. Therefore, the Grip Configuration Model allows for the identification of outliers i.e. individuals with a wider ROM than the average, and to distinguish variabilities in ADL performed.

2.2.5 Statistical Analysis

The statistical analyses of this study were evaluated using the IBM SPSS Statistics software version 25 software. To evaluate the variability between each of the joints in terms of health status, a one-way ANOVA (Analysis of Variance) was conducted. To calculate differences between the two groups between each activity, a paired t-test was conducted. This analysis determined if there were statistical differences in the way that each activity was performed by both groups. A paired t-test was also used to assess the maximum flexion/extension grip configuration, with and without the finger sleeves. A post hoc power analysis (1-β error probability) was calculated using the G*Power program [68] to determine if the type-1 (α) and type-2 (β) error probabilities were controlled for. Therefore, to determine if the sample size was sufficient in providing results that are comparable to the given population, the acceptable power level was set to 1-β>0.8 [69]. A Bland-Altman or difference plot method, paired with a linear regression, was used to indicate the overall reliability (within 95%) of the variance between the two evaluators, and within each evaluator. This ensured the accuracy of the marker placement and the joint angle evaluations. Statistical significance was considered when the P value was less than 0.05.

2.2.6 Validation

The joint angles calculated using Dartfish were validated using a manual goniometer, and an EM tracking system and an unpublished finger kinematic coordinate system. A sample of five healthy participant (aged 20-25) were recruited for validation purposes. Each participant performed three trials of maximum flexion and maximum extension of the thumb MCP and CMC, and index PIP and MCP joints. The second trial of each participant was used for the analysis calculations. Each movement was performed independently, where the participants was asked to remain static at each position of maximum flexion and maximum extension. The EM tracking system sensors were attached with a skin safe adhesive on the dorsal side of the thumb and index finger segments of the participant's dominant hand. The thumb distal phalanx, proximal phalanx, and the metacarpal, as well as the index finger distal, middle, and proximal phalanges were each identified and a single EM sensor was attached to each location (Figure 11). These landmarks were identified using the same identification tool (Bony Palpation Skill Sheet [67]) as used for identifying the landmarks for the Dartfish technique. The markers for the Dartfish analysis were placed on the ulnar side of the index finger, and radial side of the thumb. The goniometer measurements were taken by a skilled researcher with advanced experience. As the EM tracking sensors were on the dorsal side of the hand, the goniometer measurements were taken directly adjacent to the sensors location while remaining in contact with the joint segment being measured. The joint positions of the thumb MCP, and index PIP and MCP were simultaneously tracked with the EM tracking system, goniometer, and the Dartfish software (Figure 12). All three measurement values were evaluated using a univariate one-way ANOVA analysis, to ensure the Dartfish 2D video analysis software technique was appropriate for measuring the small joint angles of the hand.

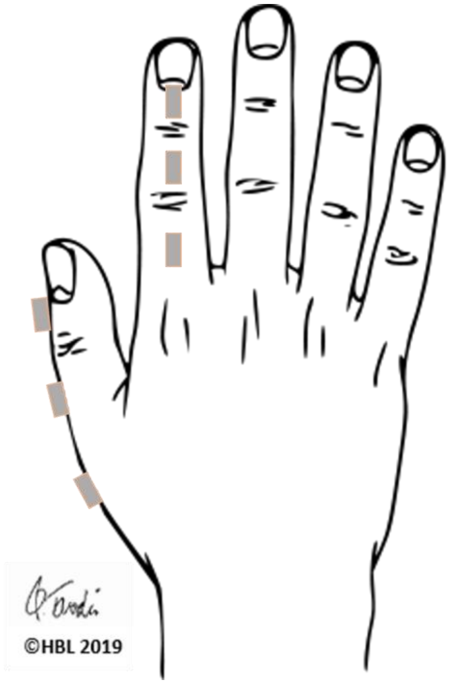


Figure 11: Electromagnetic (EM) tracking system *in vivo* sensor placement on the thumb distal phalanx, proximal phalanx, and the metacarpal as well as the index finger distal, middle, and proximal phalanges.

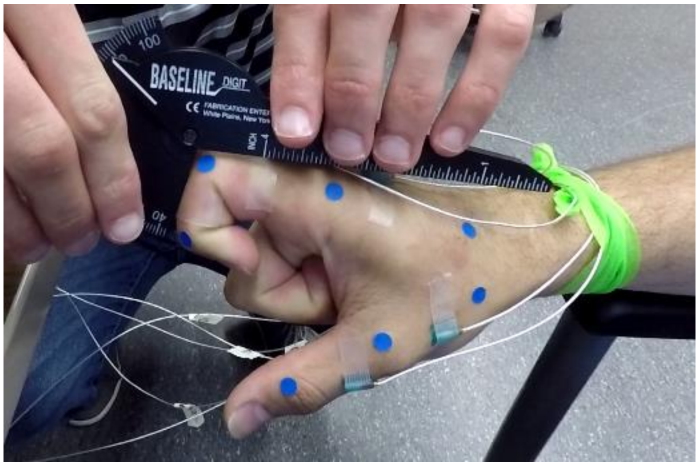


Figure 12: Validation measurement test comparing the Dartfish Movement Analysis software, the EM tracking system, and a manual goniometer.

2.2.7 Assumptions

The assumptions for this study were:

1. Movement patterns obtained by the joints of the thumb and index finger for the grip configuration model will be evaluated and assumed to represent 2D movements of flexion and extension.

2. The grip range of motion (ROM) for the hand will be defined from the angles created by the MCP and CMC joints of the thumb, and the PIP and MCP joints of the index.

3. One of the camera views will be used to obtain the 2D movement patters of each activity performed.

4. The participants with hand arthritis will be assumed to have a comparable disease severity to obtain average measures for individuals with hand arthritis (not separately evaluated by severity).

2.3 Results

Joint angles of the thumb MCP and CMC, and index MCP and PIP, were calculated using the Grip Configuration Model (healthy baseline: 0% being maximum flexion and 100% maximum extension). The average maximum flexion and maximum extension grip configurations for the individuals with hand arthritis were 17.2% [95% CI: 11.4%-23.1%; $P<0.001$] and 87.3% [95% CI: 83.4%-91.3%; $P=0.01$], respectively. This demonstrates a limitation of 17.2% for maximum flexion, and 12.7% for maximum extension in individuals with hand arthritis. These ROM results exhibit a significant difference ($P<0.05$) in individuals with hand arthritis hand movement capabilities. The values of each participant’s grip configuration for maximum flexion and maximum extension are shown below in Figure 13.

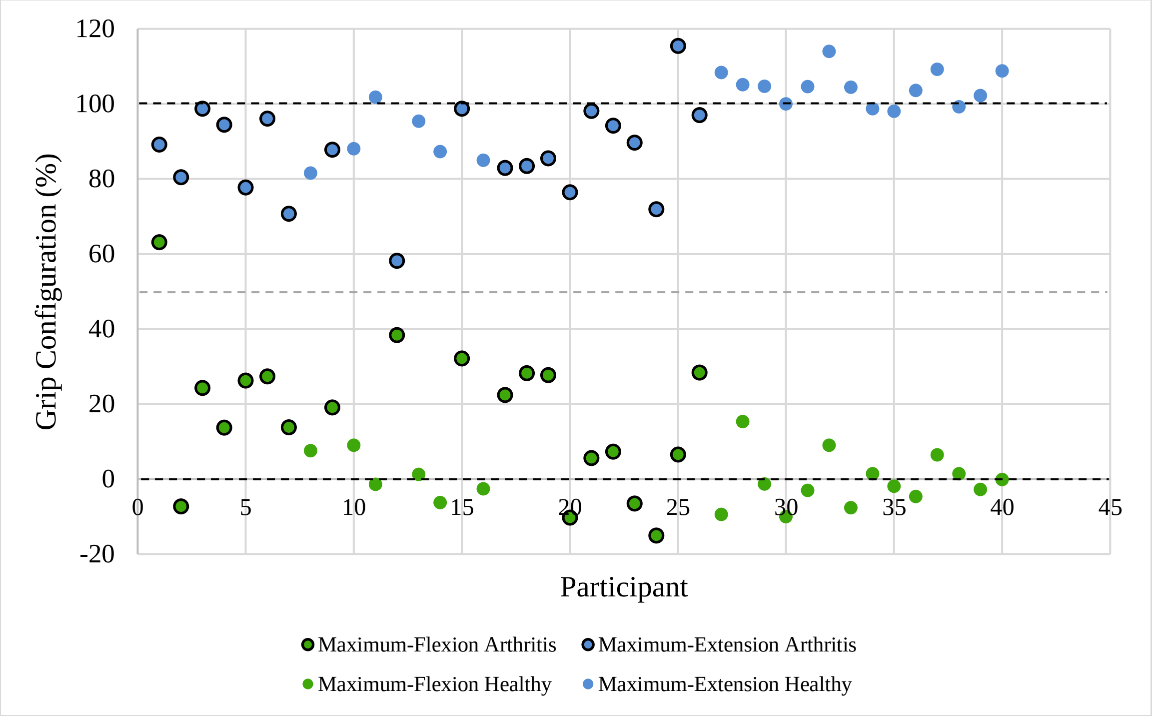


Figure 13: Maximum flexion and maximum extension grip configuration values. The horizontal dashed lines represent the healthy baseline threshold values at 0% and 100%. A mid-range is also defined at 50% with points above being in extension and below in flexion (n=20 healthy participants: n=20 participants with hand arthritis).

Grip configuration values for each of the five tasks are depicted below in Table 3. The spray bottle task showed a difference of 14.7% (P=0.001) when squeezing the trigger (flexion) and 10.4% (P=0.004) when releasing the trigger (extension) between the healthy participant and participants with hand arthritis. Grip configuration differences of 0.9% (P=0.8) for the water bottle task, 4.6% (P=0.3) for the medium diameter arthritis cap task, and 3.6% (P=0.3) for the large twist jar task were observed. These three tasks showed no significant differences (P>0.05) between the two groups. The final task of turning a key in a doorknob resulted in the individuals with hand arthritis having a 1.6% (P=0.7) more flexed position than the healthy participants. Each of the five ADL results are shown below in Figure 14.

Table 3: The average grip configuration values of the two test groups for the five activities of daily living including the positive standard deviation (SD) and upper and lower 95% confidence interval (CI) values (n=20 healthy participants: n=20 participants with hand arthritis).

Task	**Healthy Participants (%)**	**Positive SD (%)**	**Healthy Upper and Lower CI (%)**		**Participants with Hand Arthritis (%)**	**Positive SD (%)**	**Arthritis Upper and Lower CI (%)**	
Spray Bottle Flexion	44.6	16.0	75.9	13.2	59.3	16.4	93.0	28.7
Spray Bottle Extension	71.2	7.7	86.3	56.1	81.6	10.9	104.4	61.8
Water Bottle	64.7	13.1	90.4	39.0	63.8	20.2	105.5	26.4
Medicine Container	68.6	14.8	97.5	39.6	73.2	14.1	100.0	44.8
Large Diameter Jar	84.4	14.2	112.3	56.5	88.0	9.3	105.8	69.3
Turning of a Key	43.4	12.8	68.5	18.3	41.8	12.9	67.1	16.6

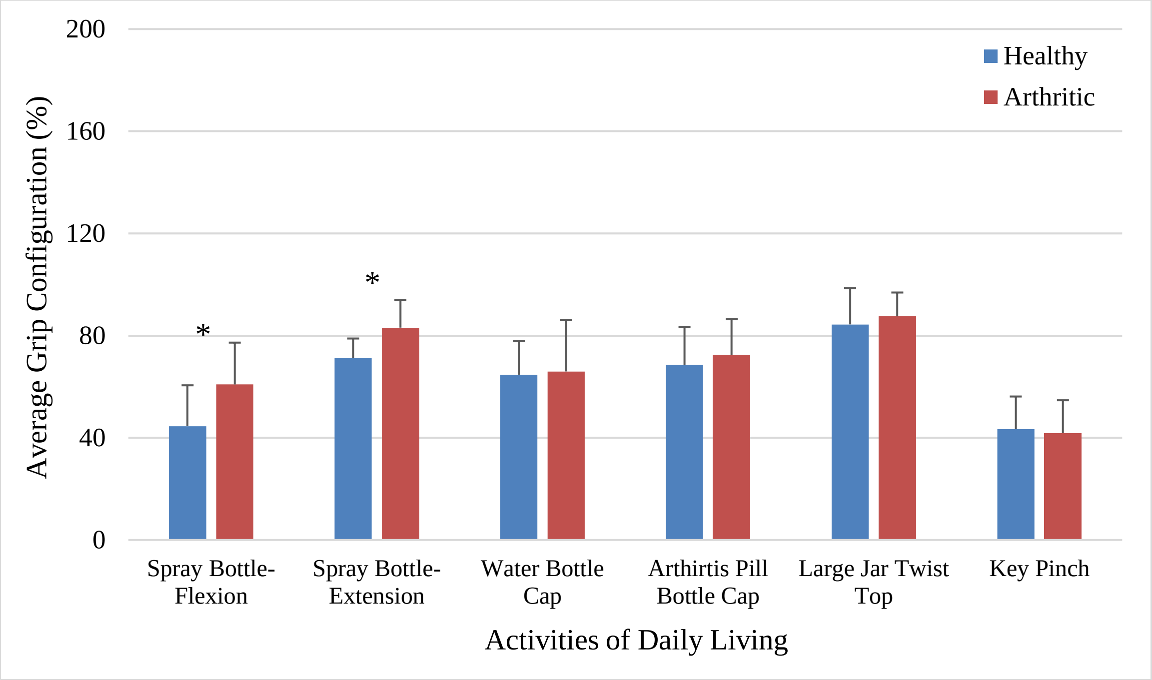


Figure 14: The average grip configuration values comparing the individuals with and without hand arthritis to demonstrate the difference between the five activities of daily living evaluated. Positive standard deviation (SD) bars and significance indications (*) are also included (n=20 healthy participants: n=20 participants with hand arthritis).

The individual joints were evaluated during maximum flexion and maximum extension between the two test groups (Table 4). For the maximum flexion joint angle measures, individuals with hand arthritis demonstrated a more extended position of 9.4° (P=0.05) in the thumb MCP joint, 8.3° (P=0.03) in the thumb CMC, 13.8° (P=0.003) in the index MCP, and 15.7° (P=0.009) in the index PIP. These results all demonstrated statistical differences. For maximum extension, only the index PIP joint demonstrated no statistical difference, with a 5.5° (P=0.2) decrease in individuals' with hand arthritis extension capabilities. All other joints for maximum extension demonstrated differences, with decreased extension angle values of 7.5° (P=0.008) in the thumb CMC, 13.6° (P=0.001) in the index MCP, and 27.3° (P<0.001) in the thumb MCP. The thumb CMC joint for maximum extension was the only joint where the individuals with hand arthritis demonstrated a larger degree of extension (7.5°). Figure 15 and Figure 16 show the average variations between the healthy participants and participants with hand arthritis for each of the joints evaluated.

Table 4: The average maximum flexion and extension angles for the index PIP and MCP, and thumb MCP and CMC joints of the healthy participants and participants with hand arthritis. The positive standard deviation (SD) values are also presented (n=20 healthy participants: n=20 participants with hand arthritis).

Joint	**Maximum Flexion**				**Maximum Extension**			
	Healthy Participants (°)	**Positive SD (°)**	**Participants with Hand Arthritis (°)**	**Positive SD (°)**	**Healthy Participants (°)**	**Positive SD (°)**	**Participants with Hand Arthritis (°)**	**Positive SD (°)**
Index PIP	67.3	9.2	83.0	24.0	173.1	11.0	167.5	14.1
Index MCP	102.0	15.0	115.8	12.3	168.0	8.9	154.4	13.4
Thumb MCP	141.7	16.3	132.2	13.5	163.2	17.1	135.9	18.3
Thumb CMC	73.3	10.6	81.6	12.6	76.5	8.3	84.0	8.5

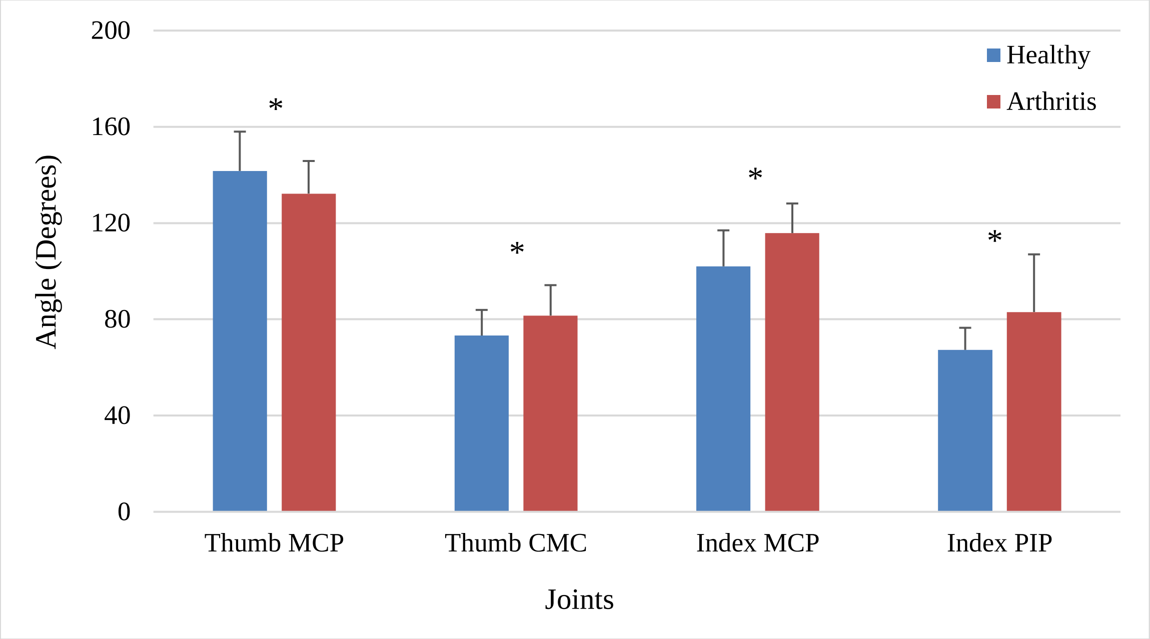


Figure 15: The average joint flexion angles comparing the individuals with and without hand arthritis to demonstrate the differences between each of the joints evaluated. Positive standard deviation (SD) bars and significance indications (*) are also included (n=20 healthy participants: n=20 participants with hand arthritis).

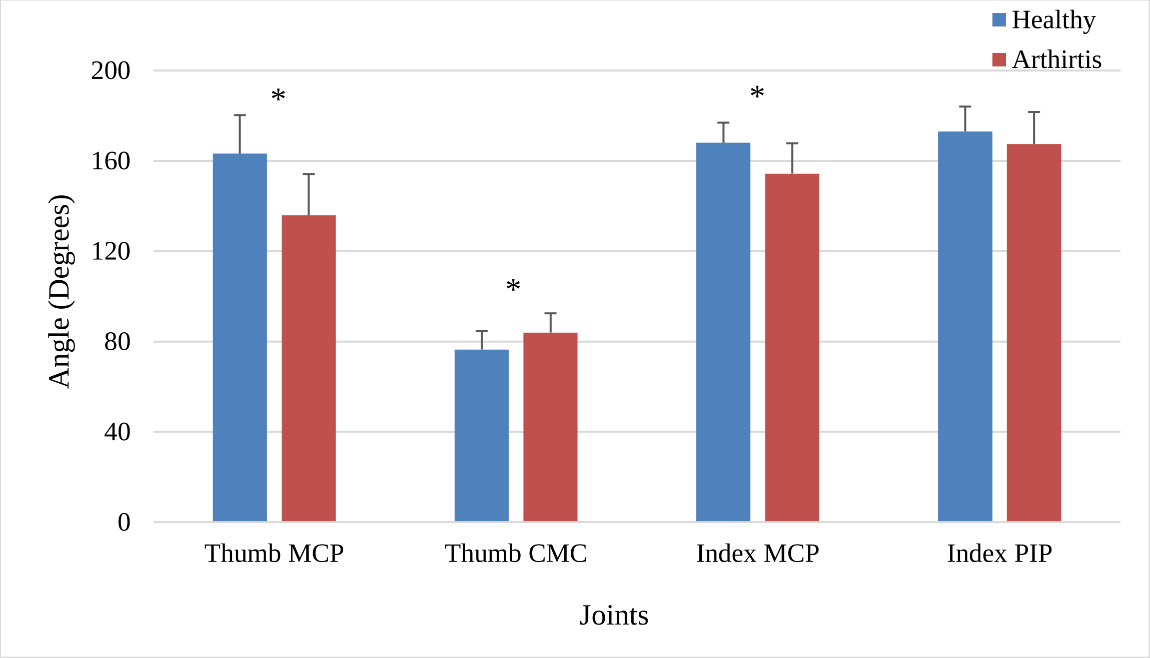


Figure 16: The average joint extension angles comparing the individuals with and without hand arthritis, to demonstrate the differences between each of the joints evaluated. Positive standard deviation (SD) bars and significance indications (*) are also included (n=20 healthy participants: n=20 participants with hand arthritis).

2.3.1 Finger Sleeves Analysis

The grip configuration values for maximum flexion and maximum extension were taken with the finger sleeves on and off to determine if there were any differences in the grip configuration results. The total population sample grip configuration values with the finger sleeves on was used. A sample of 10 healthy participants and 10 participants with hand arthritis grip configuration values with and without the finger sleeves on was taken from the main population sample. Differences in these values were calculated within the two groups using a paired t-test. The healthy group and group with hand arthritis were spit and compared separately. No difference was seen in the healthy group or group with hand arthritis for maximum flexion ($P=0.9$ and $P=0.2$, respectively) and maximum extension ($P=0.3$ and $P=0.2$, respectively). This shows that wearing the finger sleeves had no significant effect on the grip joint angle measures and therefore the configuration percentage values.

2.3.2 Reliability Analysis

In using the G*Power program, this study design was calculated to have sufficient statistical power ($1-\beta>0.8$) for both maximum flexion ($1-\beta=0.99$) and maximum extension ($1-\beta=0.95$). This concludes that the results are an appropriate representation of the population. Accurate marker placement on the joints of the thumb and index finger, were essential. This insured that the appropriate grip configuration results between the participants were obtained. The maximum flexion/extension grip configuration values, within each sample were evaluated. In both of the test groups, no statistical difference ($P>0.05$) was observed for either maximum flexion or maximum extension.

Two researchers were responsible for placing the markers on the participants' joints and evaluated the joint angles within the Dartfish Software. An inter-rater reliability and intra-rater reliability analysis was conducted to ensure no variability between or within the two raters. Each rater evaluated five participants for maximum flexion and extension with the absolute, mean, and total difference calculated for each test. In using the Bland-Altman technique paired with a linear regression analysis, the inter-rater reliability (maximum flexion $P=0.4$ and maximum extension $P=0.2$) analysis demonstrated no proportional bias between each evaluator for the maximum flexion/extension activity as the data points were within the 95% limit bounds (Figure 17 and Figure 18). The same analysis was used for the intra-rater reliability (maximum flexion P=0.9 and maximum extension P=0.3), with results for evaluator 1 demonstrating no differences for the maximum flexion/extension activity as each of the data points were within the 95% limit bounds (Figure 19 and Figure 20). Therefore, this legitimizes the joint angle measurement results obtained in this Chapter.

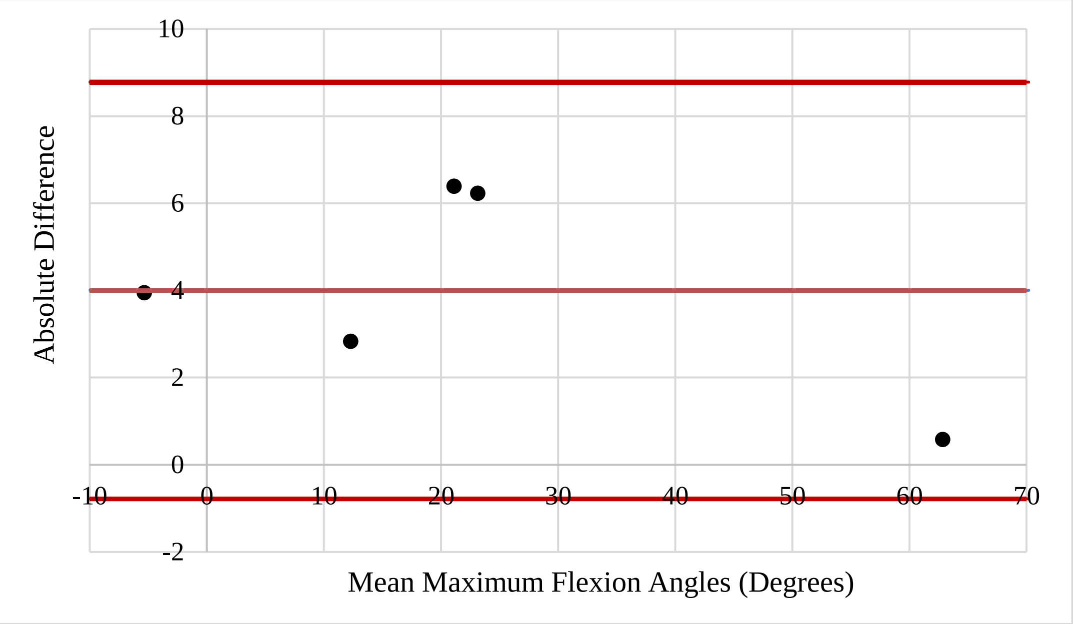


Figure 17: Bland-Altman Graph for the inter-rater reliability analysis for maximum flexion activity. The upper and lower 95% are represented by the horizontal red lines, calculated from the mean flexion angle values between each rater for the five trials and the total mean within both raters. The total mean value is represented by the horizontal blue line.

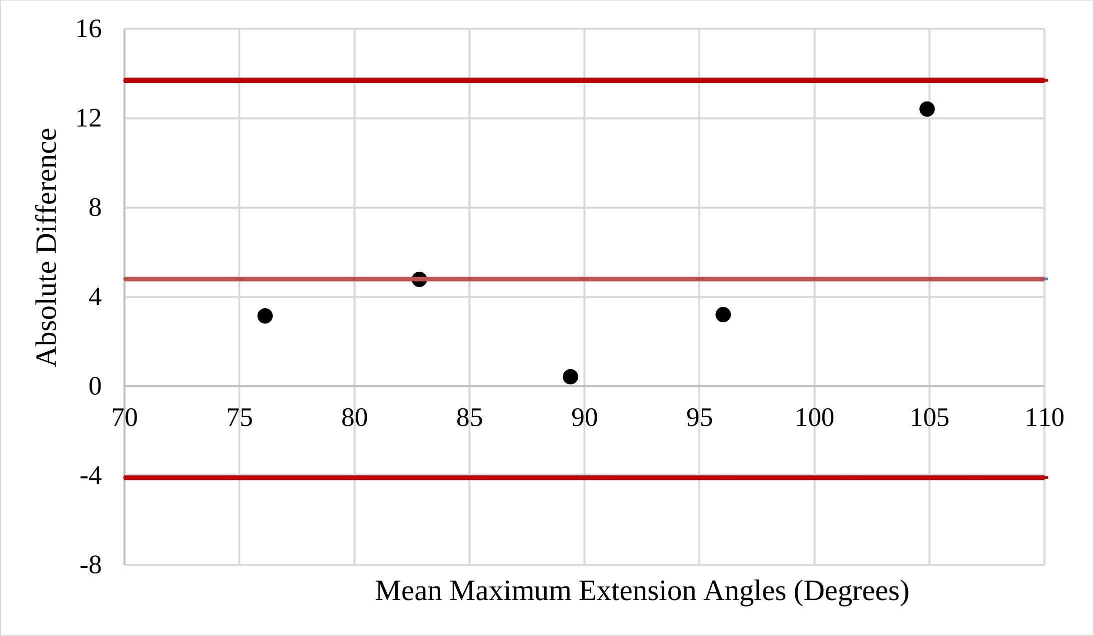


Figure 18: Bland-Altman Graph for the inter-rater reliability analysis for maximum extension activity. The upper and lower 95% are represented by the horizontal red lines, calculated from the mean flexion angle values between each rater for the five trials and the total mean within both raters. The total mean value is represented by the horizontal blue line.

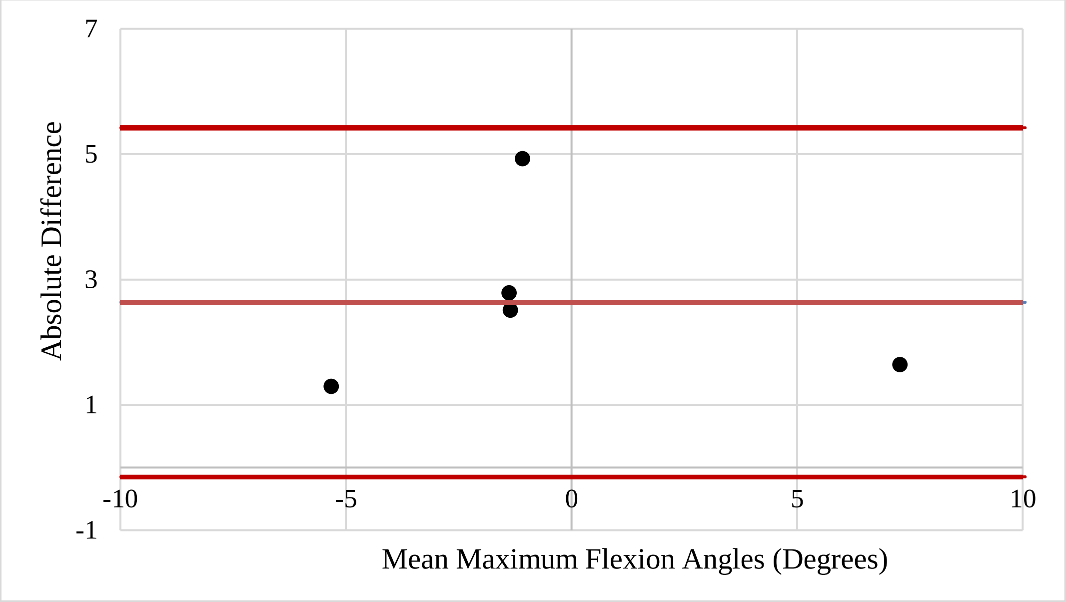


Figure 19: Bland-Altman Graph for the intra-rater reliability analysis for maximum flexion activity. The upper and lower 95% are represented by the horizontal red lines, calculated from the mean flexion angle values between each rater for the five trials and the total mean within both raters. The total mean value is represented by the horizontal blue line.

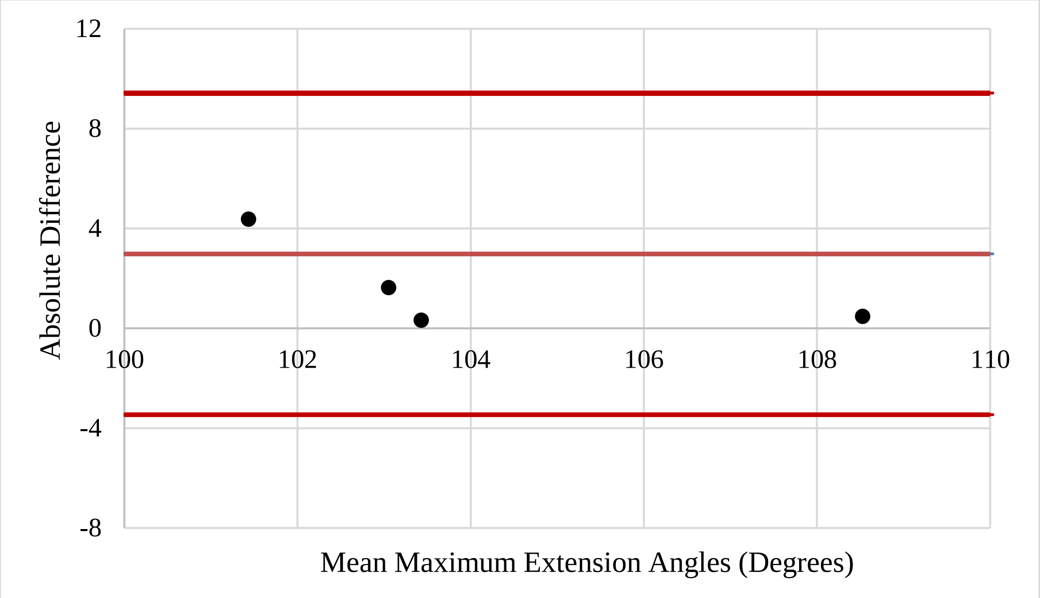


Figure 20: Bland-Altman Graph for the intra-rater reliability analysis for maximum extension activity. The upper and lower 95% are represented by the horizontal red lines, calculated from the mean flexion angle values between each rater for the five trials and the total mean within both raters. The total mean value is represented by the horizontal blue line.

The kinematic motion analysis technique of the Dartfish Movement Analysis Software was compared against two other techniques being a digital EM tracking system, and a manual goniometer. The index PIP and MCP, and thumb MCP joints, were evaluated when preforming maximum flexion and maximum extension. A sample of five healthy participants aged 20-25 years (four right hand dominant and one left hand dominant) were recruited with three trials conducted for each movement. The results calculated from the one-way ANOVA analysis demonstrated no statistical difference between any of the three measurement techniques for the index PIP (P=0.3, 1-β=0.2), index MCP (P=0.05, 1-β=0.6), and thumb MCP (P=0.1, 1-β=0.4) range of motion. This analysis was not without challenges. The EM tracker wires which mount onto the anatomical landmarks, were bulky and took up a large amount of surface area on the dorsal aspect of the hand. This made it difficult to place the reflective markers on the participant's joint locations for the Dartfish analysis. Also, while measuring the small joints of the hand, ensuring that the goniometer was appropriately placed was constantly monitored to obtain correct measurement values. This analysis also did not have sufficient power (1-β) as each test resulted in a power less than 0.8, therefore potentially causing errors in the statistical evaluations.

2.4 Discussion

The main research question of this study was to determine if there were significant differences in individuals with and without hand arthritis (specifically OA) ROM capabilities, and when performing various ADL. The purpose of this Chapter was to develop and validate (using a manual goniometer and EM tracking system) a simple, video-based motion analysis measurement technique, to quantify the hand’s grip joint range of motion (Grip Configuration Model) to evaluate kinematic changes of the hand (Objective 1a.). Movements during maximum flexion and maximum extension (Objective 1b.i.), and five functional tasks (Objectives 1b.ii.) were examined to detect diversity between groups of individuals was evaluated.

Eltoukhy *et al.* conducted a statistical analysis on the performance of the 2D Dartfish tracking software, on its ability to obtain results of simple gait motions, comparable to other 3D motion capturing systems such as Vicon [70]. Passive markers were placed on the lateral and posterior sides of the lower back (hips) and both legs to identify the joints of the hips, knees, and ankles [70]. It was concluded that the 2D motion capture software has potential to generate high quality values. However, the Dartfish Software is limited to only being able to analyse motion in a single plane without combining camera views in 3D. The hand moves in multiple planes often simultaneously, therefore obtaining accurate measurements during functional tasks is difficult. In this study, all attempts were made to standardize the camera positions, and marker placement for ROM measures. The introduction of the Grip Configuration Model, simply quantified the magnitude of the grip ROM differences seen in individuals with hand arthritis. Previous studies on grip ROM and ADL, have all produced similar results using a variety or tools and techniques. Techniques previously used include optoelectronic motion analysis [15], digital photographic imagery [17], pressure-sensitive sheets [14], and instrumented gloves [16]. This current study used less expensive, simpler techniques, to produce similar results. This allowed for a more comprehensive evaluation of the gripping/grasping movement than presented in previous literature.

The results of this study obtained using the Dartfish Movement Analysis Software were compared against a digital EM tracking system and manual goniometer. No statistical difference between the three measurement systems was observed for the thumb MCP joint measurements. However, this analysis also did not have sufficient statistical power (1-β) as each test potentially causing errors in the statistical evaluations. Other limitations were also evident in this study. Dartfish is a 2D software, which imposes restrictions of only being able to evaluate ADL that involve flexion and extension. Movements involving deviation of the joints, such as radial and ulnar deviation, were unable to be simultaneously captured. Due to the camera angles, and the way in which some tasks were performed, many of the markers were out of the camera's line-of-sight. This resulted in the exclusion of participant's data, as the aim was to have complete data sets for each participant. The angle measure of the DIP joint of the index finger was also excluded, due to its small size and often being hidden from the view of the cameras. Khadilkar *et al*. expressed that using high definition cameras would prove higher accuracy when analysing images in the Dartfish software [64]. Each of the cameras used in this current study were of high quality.

The results of this study showed that individuals with hand arthritis have a limitation in their average maximum flexion/extension grip capabilities of roughly 15%. The ADL that showed a significant difference between individuals with and without hand arthritis was the spray bottle task, demonstrating an average limitation of roughly 13%. Compared to the healthy participants, the participants with hand arthritis hyper-extending when releasing the trigger of the spray bottle. When the trigger was pulled (spray bottle handle was squeezed), a limitation in the flexion capabilities was found. This limited flexion capabilities in the individuals with hand arthritis sample could be due to the joint location of the participants' OA. It was also recognized that the individuals with hand arthritis dominantly used their index PIP joint to perform the spray bottle task, rather than utilizing multiple joints of their thumb and index finger as the healthy population did. This shows the potential preservation of other joints of the hand by using the minimum amount required to perform the task. The grip configuration results for the small, medium, and large diameter size twist lids, and for the turning of a key in a doorknob task, had no significant differences between the two groups. This indicates that rigid tasks dominantly defined by their shape, produce similar grip configurations in individuals' both with and without hand arthritis.

Variations in gripping styles were seen when observing each participants technique to complete each task. For maximum flexion, a normal fist position was defined as having the thumb wrapped underneath the index finger DIP joint (laying on top of the dorsal aspect of the DIP joint). An overlapping fist position was defined as having the thumb lay over top of the medial side of the index finger DIP/PIP joint shown in Appendix B1 and B2. In the healthy participants, only 10% of the sample performed the overlapping gripping style, with no difference found between the two styles (P=1.0). The participants with hand arthritis had a larger portion (30%) that performed the overlapping gripping style, possibly due to their reduced ROM capabilities. Even with this increased percentage, no difference was observed between the two gripping styles (P=0.2). This analysis was also done for the large diameter jar task comparing a fingertip and palm-gripping style shown in Appendix B3 and B4. Thirty (30) percent of the healthy participants, and 20% of the participants with hand arthritis performed this task by dominantly using their palm to open the jar. No difference was found between the fingertip gripping style (P=0.5) and the palm gripping style (P=0.7) in either test group.

The use of the Grip Configuration Model and Dartfish Movement Analysis Software, gives the potential for clinical applications. It provides better evaluations of the movement patterns seen in the small joints of the hand during ADL, work related tasks, and recreational activities. To further progress this area of research, continued assessments and implementations of new techniques needs to be explored. This study protocol, and the use of both the Grip Configuration Model and Dartfish Movement Analysis Software, could be used to evaluate every joint in the hand to obtain a complete kinematic analysis of the hand. By establishing accurate, qualitative results for the movements of the hand during ADL in individuals with and without hand arthritis, more sophisticated biomechanical models can be developed. These models would allow for estimations of the internal muscle, ligament, and tendon loadings of the hand, to better understand the effects of joint diseases such as OA.

2.5 Conclusion

Results from this study concluded that participants’ with hand arthritis (specifically OA) experience a reduced ROM, compared to the healthy participants. A limitation in individuals with hand arthritis grip (or variation) of 17.2% in maximum flexion (making a fist) and 12.7% in maximum extension was found. Range of motion is one of the crucial functions of the hand. Limitations in this function cause difficulties in every aspect of one’s life. The results of this study and the development of the Grip Configuration Model, gives insight into how people perform ADL, and how this changes in the diseased state. Further evaluations need to be conducted with a larger sample size to further assess the movements of the hand when performing specific daily living tasks or using various tools and recreational equipment, in order to reduce the potential overexertion of the joints of the hand.

The hypothesis of this study stated in Chapter 1 was that functional limitations in range of motion in individuals with hand arthritis will be translated to activities of daily living (Hypothesis 1). This was proven to be true in the spray bottle task. However, small variations were observed in the grip configuration results of the three different diameter twist tops, as well as for the key pinch task between the individuals with and without hand arthritis. This however does not mean that these tasks were easy for the participants with hand arthritis to perform. It does however demonstrate that for certain ADL, finding alternative grasping techniques to perform a specific task is difficult. Therefore, alternative techniques and tools for a variety of ADL and recreational activities, should be properly tested, designed, and implemented to appropriately support individuals with hand arthritis joints. It is theorised that the current alternative techniques and tools designed for individuals with hand arthritis to assist them when participating in different recreation activities such as golf, do not hold true to their claims. To determine whether this is the case, further investigations will be done in relation to the recreational activity of golf, and expand the analysis to evaluate golf grip force.

Chapter 3 – Investigating the Grip Forces Exerted by Individuals with and without Hand Arthritis while Swinging a Golf Club with the Use of a New Wearable Sensor Technology

3 Overview

In the previous chapter, we investigated the ROM differences seen in individuals with hand arthritis when performing the simple action of maximum flexion/extension, as well as during five ADL. Having developed the Grip Configuration Model to simply quantify these ROM differences, the exploration into recreational activities such as golf can be easily done. Golf is a low-impact, dynamic sport that assists both younger and older individuals in maintaining a healthy and active lifestyle. A golfer's grip and the design of the golf grip itself, are key components to the biomechanics of the golf swing. As the hands are the only contact point between the player and the club, the design of the golf grip greatly influences a golfer's grip. This chapter will use the Grip Configuration Model introduced in Chapter 2 to evaluate the golfer's grip configuration when gripping a sample of 12 standard and 'arthritic' designed golf grips. A commercially available finger force sensor system was also employed to examine the grip forces exerted onto the 12 golf grips tested.

3.1 Introduction

In Canada, over six million people have arthritis [21]. Arthritis is a disease that causes degradation of the joint structure, resulting in pain, swelling, and stiffness. A common location for arthritis to occur is the hands, which results in a weakened grip ROM and strength. Grip ROM differences in individuals with hand arthritis was quantified in Chapter 2. Based on the results of this previous chapter, people who suffer from hand arthritis demonstrated a 17.2% grip configuration limitation for maximum flexion (making a fist) and 12.7% for maximum extension. This weakened function of the hand makes it difficult to perform various ADL, vocational, and recreational activities. Chapter 2 also investigated several ADL and demonstrated that the simple limitations seen in individuals with hand arthritis maximum flexion/extension capabilities, was translated to some of these activities. In this chapter, the task is to evaluate if this translation holds true during the recreational activity of golf, and to pair this assessment with the investigation of players' golf grip force.

The inability to participate in recreational activities can lead to sedentary behaviour, which is counterproductive to one's health as participating in regular physical activity can assist in maintaining healthy joint function. For individuals with joint diseases such as arthritis, regular physical activity can minimize the symptoms associated with such a disease. Golf is considered a low-impact sport that can be played at any age. Over 35% of the golfing population are over 50 years of age [71]. With over 70% of the population who have hand arthritis being over 50 years of age [72], it presents a possible relationship between people who play golf and have hand arthritis. Clinicians often recommend golf as an activity for older adults to help maintain a healthy lifestyle. However, if the proper equipment and techniques are not in place to assist these individuals, this may not be an appropriate recommendation.

New training techniques and equipment in the golfing industry have been designed to assist with player's golf swing development. TrackMan is a device used to record various components of the golf swing, including ball flight, club face angle, and club speed to provide players and coaches a measureable quantity of a player's performance [73]. Measurement devices have also been developed to specifically evaluate golfers' grip forces. An instrumented golf club was designed using strain gauge sensors installed underneath the golf grip of a standard driver [74]. The grip forces of both a professional and amateur golfer were evaluated with the professional player demonstrating a lighter overall grip force than the amateur player [74]. With the force sensors being underneath the golf grip, and the two golfers hand placements not standardized, it presents the possibility of the golfer's hand location on the grip not being consistent within and compared to each participant. This would result in different groups of fingers being measured during each swing. Another study employed an F-scan^R mobile research system (Tekscan version 5.72, Boston Mass) consisting of ultra-thin, flexible force sensors, attached to a golfer's own grip [75]. In using an ultra-thin pressure sensitive film, it provided a minimally invasive solution limiting the amount of excess material between the hand/golf grip interface [75]. However, common issues with pressure sensitive films are that they can wrinkle and bend easily. This could result in inaccuracies, and require constant re-adjustments of the sensors' position.

Komi *et al.* designed two glove sensors to measure golfers' grip forces, by fixing the gloves with a total of 31 individual light-weight, thin-film force sensors [57]. The sensors were easily able to bend and contour around the palmar side of a golfer's hand when gripping the golf club [57]. This technique provided force measurements at numerous locations simultaneously. It was observed that each golfer had a very repeatable grip force trace, with noticeable patterns found between the local maxima and minima [57]. The benefit of this technique is in knowing the specific hand location of the forces exerted onto the grip of the club. However, in using two gloves, it would add excess material bulk, particularly as the fingers are in a flexed position when gripping a golf club, greatly restricting the participants ROM capabilities. During the golf swing, large shear forces occur at the hand/grip interface. With the sensors being directly in contact with the golf grip, there is a high possibility of sensors dislocating from the gloves, which would present inflated results.

In the current literature, there is only one study conducted in 1991 which evaluated the biomechanics of the golf swing in players with a variety of upper limb disorders, with one being hand arthritis [76]. Cahalan *et al.* compared a straight-handled golf grip to a BioCurve grip with no differences seen on club impact force, location of impact on the club face, club head velocity, club head path, or face angle between the two grip designs [76]. Since, Cahalan *et al.* [76] did not control for a single upper limb disorder, it would suggest that the data is skewed as different upper extremity diseases cause different musculoskeletal changes and therefore different biomechanical limitations. With the continual increase in the aging population, and a common disease among golfers being hand arthritis, the need to conduct comprehensive evaluations and develop strategies based on qualitative data to assist these individuals is crucial.

A small portion of golf manufacturers have begun to market 'arthritic' designed grips. Notable companies such as Lamkin and Tacki-Mac have designed a unique serrated, or 'nubbed' texture 'arthritic' golf grip. Designed to promote a reduced grip force through the increase in tactile feedback, and increase the friction coefficient between the hand/golf grip interface [77]. Soft firmness, oversized diameter grips, are another design that has become popular amongst individuals with hand arthritis [78]. This design provides support through a soft feel, and reduces the grip ROM required [78]. Other assistive devices such as gloves and braces have been designed to stabilize the joints of the hand. The company Quantum Grip, designed a Velcro glove/grip combination, which claims to greatly reduce muscle fatigue, has shock enhancing power, and increases club stability [79]. Many of these assistive devices and 'arthritic' grips are not widely advertised, and lack the quantitative evidence to support their claims. Therefore, the purpose of Chapter 3 was to utilize the Grip Configuration Model to quantify the golf grip range of motion differences in individuals with and without hand arthritis (Objective 1b.iii.), and employ a commercially available force measurement system (Objective 2) to detect differences in golfers total grip force when swinging golf clubs with a variety of 12 standard, and 'arthritic' designed golf grips (Objective 3).

3.2 Study Protocol

3.2.1 Participants

Twenty seven (27) participants (17 healthy participants: 10 participants with hand arthritis) were recruited for this study. The demographics for this study population is demonstrated below in Table 5. The healthy participants consisted of both right and left handed golfers. The sample with hand arthritis consisted entirely of right handed golfers. From this cohort, 18 of the 27 participants (10 healthy participants: 8 participants with hand arthritis), were additionally evaluated for their grip configuration (ROM) for the 12 grips. The Patient Rated Wrist/Hand Evaluation was used to rate the participants pain and disability in their wrist and hand, as well as functional difficulties when performing various ADL [65]. In this study, a total score below 20 classified participants as having none or minimal pain/disability, a score between 20 and 80 was considered to have a moderate level of pain/disability, and a score above 80 was identified as extreme pain/disability. This allowed for the degree of wrist/hand related musculoskeletal disabilities to be quantified within the two test groups [66].

Table 5: Demographic of Chapter 3 golf grip force population.

	Healthy Participants	**Participants with Hand Arthritis**
Gender		
Male	11	4
Female	6	6
Age		
18-35	9	0
36-50	4	0
51-65	4	4
65+	0	6
Hand Dominance		
Right	16	8
Left	1	2
Hand Golfer		
Right	13	10
Left	4	0
Golf Glove		
Right	5	0
Left	6	5
Both	1	4
Neither	5	1
Golf Gripping Style		
Interlocking	8	4
Overlapping	2	3
Baseball (10 Finger)	7	3
Form of Arthritis		
Osteoarthritis	0	10
Rheumatoid Arthritis	0	0
Psoriatic Arthritis	0	0
Patient Rated Wrist/Hand Evaluation (PRWHE)		
No Pain (PRWHE < 20)	14	1
Moderate Pain (20 < PRWHE < 80)	3	8
Extreme Pain (PRWHE > 80)	0	1
Years Arthritis Diagnosis		
1-10	0	5
10+	0	5

All of the individuals with hand arthritis, indicated that they had been previously diagnosed by a clinician with hand arthritis, specifically OA. The 17 healthy individuals had no previous diagnosis of hand arthritis. Participants were excluded if they did not have adequate golf experience (do not play or go to a golf range approximately two times a year), were under the age of 18, had any other medical conditions affecting their hand function, or any hand or wrist injuries within the last year. Western University's Research Ethics Board approved this study protocol (Appendix H).

3.2.2 Data Collection

3.2.2.1 Golf Grips

Twelve (12) standard and 'arthritic' designed golf grips were evaluated. Each grip was fitted onto a mid-iron (7-iron) golf club with two full swings performed with each club. The study was conducted in a Biomechanics Laboratory, hitting a golf ball off artificial turf into a net (Figure 21). The group of grips consisted of nine standard designed grips manufactured by Golf Pride and three 'arthritic' designed grips, ranging in material composition and geometry (diameter) size. The material compliance of each of the 12 golf grips was calculated using a type A durometer (ASTM 2240). The 12 standard and 'arthritic' golf grips evaluated are displayed below in Figure 22, with Table 6 presenting the basic properties of each grip.

Figure 21: Golf study test set-up in the Thames Hall Biomechanics Laboratory at Western University.

Figure 22: The 12 golf grips tested in this study from left to right: CP2 Pro Undersized, CP2 Pro Standard, CP2 Pro Mid-Sized, CP2 Pro Jumbo, MCC PLUS4 Undersized, MCC PLUS4 Standard, MCC PLUS4 Mid-Sized, Z-Grip Standard, Z-Grip Mid-Sized, Tacki-Mac Arthritis Serrated Standard Grip, Winn Excel Soft Oversized Grip and Lamkin Arthritis Grip.

Table 6: The 12 standard and 'arthritic' designed golf grips used for testing, with material, and geometry (diameter) size categorization. The grip order presented (top to bottom) pairs with the grip order from left to right in Figure 22 [54], [77], [80], [81].

Grip Name	Material Categorization	Geometry Size
CP2 Pro	Soft Firmness	Undersized
		Standard
		Mid-Sized
		Jumbo
MCC PLUS4	Medium Firmness	Undersized
		Standard
		Mid-Sized
Z-Grip	Hard Firmness	Standard
		Mid-Sized
Tacki-Mac Arthritis Serrated Standard Grip	Medium Firmness	Standard
Winn Excel Soft Oversized Grip	Medium Firmness	Mid-Sized
Lamkin Arthritis Grip	Medium Firmness	Standard

This selection of grips was chosen as they cover the spectrum of golf grips currently on the market. In evaluating a variety of grip designs, it allowed for a detailed analysis of the grip forces exerted onto the different designs of grips. The nine standard designed grips were manufactured by Golf Pride. Golf Pride is one of the top grip manufacturers in the industry, using rubber, hybrid, and corded materials to design a variety of grips. These materials provide durability in a range of surface textures and firmness [78]. The CP2 Pro soft performance grips, are rubber grips built for comfort and control, allowing for a lighter grip force and has vibration dampening properties [82]. This soft rubber grip design is made for dry weather conditions to provide a high friction coefficient between the hand/grip interface. The MCC Plus4 medium firmness (hybrid material) grips, contains two materials (rubber and corded) to create the best combination of moisture management and feel [82]. Many other golf companies use the MCC PLUS4 standard diameter grip on their clubs for initial sale/distribution. The Z-Grip hard firmness grips, consist of a corded material design to provide a higher friction coefficient between the hand/grip interface [78]. Similar to the soft rubber grip design which provides better traction in dry weather conditions, the firm corded grip design is made for wet weather conditions. The three ‘arthritic’ designed grips are the Lamkin arthritis grip, the Tacki-Mac arthritis standard grip, and the Winn oversized soft firmness grip. The Lamkin and Tacki-Mac grips are designed with a unique serrated or ‘nubbed’ texture to increase tactile feedback promoting a lighter grip force [77]. This ‘nubbed’ texture design also increases the surface area in contact with the player’s hand, therefore increasing the friction coefficient providing better club security. The Winn oversized soft firmness grip is a wrapped design grip, with a soft surface texture, providing a tacky feel similar to the CP2 soft firmness grip design [78].

3.2.2.2 Equipment Set-Up and Procedures

To measure the grip ROM and force of a golfer’s grip, two different technologies were used. The Dartfish Movement Analysis Software was used to measure the joint angles of each player’s golf grip configuration. The Finger Tactile Pressure Sensors (FingerTPS) designed by Pressure Profile Systems (PPS, Los Angeles, CA, USA) measured the forces at the fingertips during the swing. This section will provide details on these techniques, and how they were used in this study.

3.2.2.2.1 Dartfish Movement Analysis Software

As discussed in Chapter 2, the Dartfish Movement Analysis Software is an optical, kinematic tracking system, which uses 2D markers to record joint movement [63]. A commercially available GoPro Hero 5 video camera, was used to capture the static joint angles of the golfer's gripping style for each of the 12 golf grips. When capturing each image, the camera was oriented perpendicular to the joints being measured. This was subjective to the single evaluator as each participant had a slightly different grip orientation. Small 0.6mm removable markers, were placed on anatomical landmarks of the participant's bottom gripping hand (the hand closer to the head of the club) thumb and index finger. The joints pinpointed were: the metacarpophalangeal (MCP), carpometacarpal (CMC), and interphalangeal (IP) joints of the thumb; the distal interphalangeal (DIP), proximal interphalangeal (PIP), and MCP joints of the index. A second set of markers were placed on the ulnar side of the thumb IP joint, and the radial side of the index DIP, PIP, and MCP joints. Anatomical landmark locations were assessed by a single evaluator in the same manner as discussed in Chapter 2 section 2.2.2.2.

3.2.2.2.2 Pressure Profile Systems (PPS) Finger Tactile Pressure Sensors (FingerTPS)

The FingerTPS system was used to measure the forces at the distal palmar aspect of the thumb, index, middle, and ring finger, in each participant's bottom gripping hand (the hand closer to the head of the club). This technology has a sampling rate of 50HZ, pressure range of 0-10 psi, and pressure resolution of 0.01 psi [83]. These sensors use capacitive technology encompassed into a minimally invasive, micro spandex finger cot that can easily slip over the individual finger and thumb segments [83]. A capacitive sensor is designed using two metal electrode plates, separated by a proprietary compressible dielectric matrix [82]. The FingerTPS system electrodes, are arranged in the matrix as orthogonal, overlapping strips [83]. This creates a distinct capacitor at each overlapping point, providing excellent repeatability and sensitivity [83]. When a force is applied to the sensor, an electric charge is generated and stored. Each finger sensor is plugged into the signal conditioning wrist assembly (Figure 23) which collects the stored information from each finger sleeve capacitor. The signal conditioning wrist assembly then passes the information to the rechargeable electronic interface module (D710 interface) (Figure 24) being connected by a single long wire. The rechargeable electronic interface module communicates wirelessly via Bluetooth, to a computer running the Chameleon Visualization Software (Figure 25) designed by Pressure Profile Systems specifically for the FingerTPS system [83]. The Chameleon software creates a calibration equation to convert capacitance values from the sensors to force in Newtons (N). This is accomplished through the process of calibrating each finger sensor prior to testing using a single degree-of-freedom load cell designed by PPS. During testing, the software selectively scans through the outputted array at high speeds, measuring the local force at each electrode [83]. The software then displays a single graph exhibiting the force change in Newtons (y-axis) in terms of the time in seconds (x-axis) from the start of the test, with each active sensor represented by a different coloured line. The sensors versatility has been used to assess the mechanical response of the hand when operating hand power tools [84], and to show that using a cursive writing style exerts higher forces in the fingers then when using a non-cursive writing style [85]. The company has also demonstrated the sensors use during different sporting activities such as football, baseball, and basketball [83].

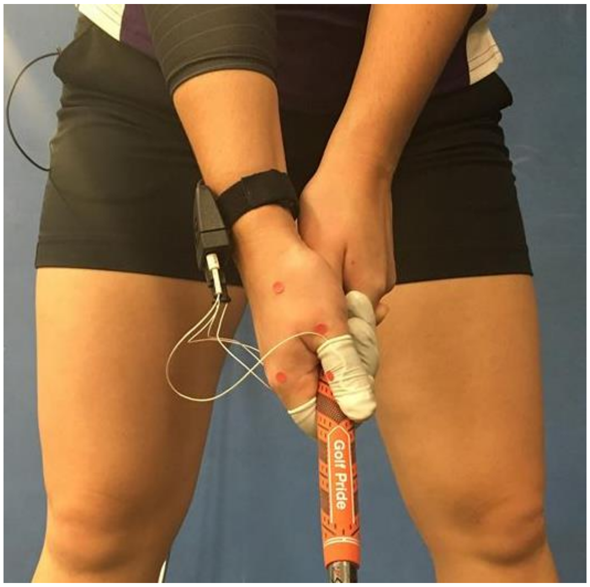
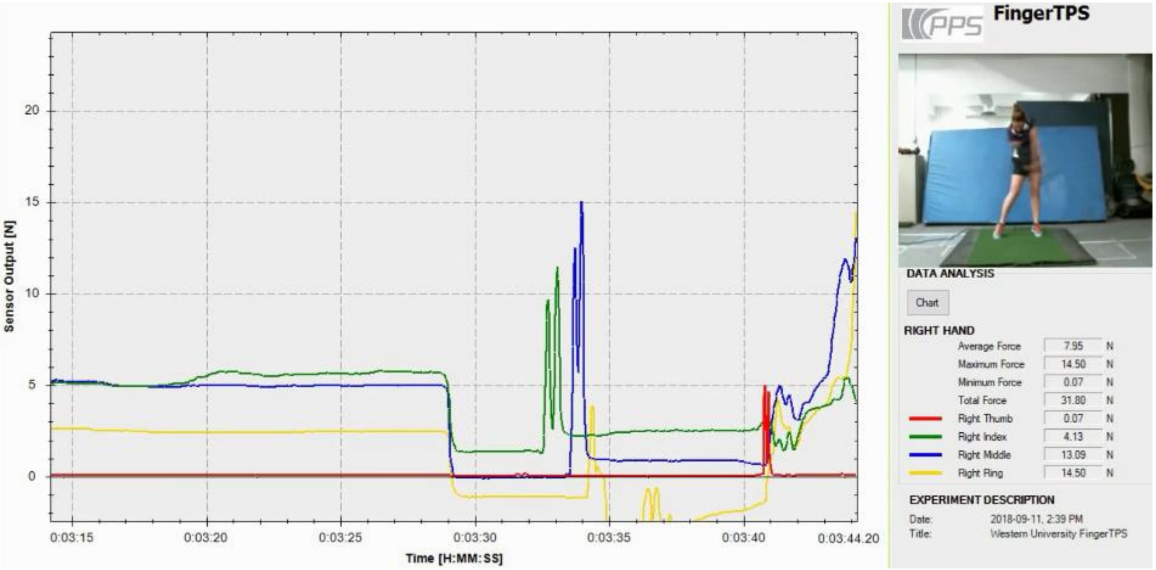


Figure 23: FingerTPS sensors on the bottom gripping hand of a golfer’s thumb, index, middle, and ring finger. The signal conditioning wrist assembly is secured to the golfer’s wrist by a Velcro strap.

Figure 24: The rechargeable electronic interface module (D710 interface) attaches to a belt or the waistline of the participant's pants and is responsible for transmitting the data collected by the finger sensors to the computer through Bluetooth.



DATA ANALYSIS

RIGHT HAND

	Average Force	7.95	N
	Maximum Force	14.50	N
	Minimum Force	0.07	N
	Total Force	31.80	N
🟥	Right Thumb	0.07	N
🟩	Right Index	4.13	N
🟦	Right Middle	13.09	N
🟨	Right Ring	14.50	N

EXPERIMENT DESCRIPTION

Date: 2018-09-11, 2:39 PM
Title: Western University FingerTPS

Figure 25: The Chameleon Visualization Software displays a graph showing the force changes in Newtons (N) over time (s) when a force is applied to each sensor.

3.2.2.3 Protocol

Prior to study participation, each participant signed a consent to participate (Appendix D), and completed a short survey to gain general background information about the participant's golf game and hand arthritis status (Appendices E1). Each participant's bottom gripping hand (right hand for a right handed player and left hand for a left handed player), measurements were taken for hand length (from the base of the palm to the tip of the middle finger), middle finger length, breadth, span, and web. For hygiene purposes, a latex finger cot was first placed on the participant’s bottom gripping hand thumb, index, middle, and ring finger. Appropriately sized FingerTPS sensors, were slipped over each of the fingers which had a latex finger cot on. Finally, a second layer of the latex finger cots were placed over top of the sensors to provide protection to the sensors from the high shear forces experienced during a golf swing. Each sensor has a single wire connecting to the signal conditioning wrist assembly which is securely wrapped around the participant’s wrist via a Velcro strap. A single, long wire, ran up the participant’s arm and down their back connecting the signal conditioning wrist assembly to the rechargeable electronic interface module. An athletic compression sleeve was placed over the participants’ forearm, preventing the wire from interfering with the participant’s swing during testing. The lightweight rechargeable electronic interface module, was attached to the participant’s waist, either by a belt or onto the waistline of their pants. Once the system was active, a single degree of freedom load cell designed by Pressure Profile Systems Inc., was used so that the program could convert each individual sensor output from capacitance to force in Newtons (N). Each participant was instructed to individually place a finger sensor onto the center of the load cell, with as much of their fingertip pad in contact with the load cell as comfortably possible. This ensured that the entire surface of the capacitor was in contact with the load cell. The participants were then instructed to gradually increase the linear force applied onto the load cell until they reached a set average threshold of 15N. These steps were repeated for each active sensor.

Each participant was first evaluated for their regular and maximum golf grip strength, using the MCC PLUS4 (medium firmness) standard diameter grip. The participants were asked to grip the club as they normally would to perform a golf swing (regular golf grip strength). They were then instructed to grip the club as tight as they could (maximum golf grip strength). Two trials were conducted for each grip strength activity, holding each position for a length of three seconds. Each of the 12 grips were randomized for each participant. Two swings, hitting a golf ball off of artificial turf into a net, were performed with each grip. Before each swing and the regular and maximum golf grip strength activity, the finger sensors were zeroed. This was done by instructing the participants to hold their hand with the sensors, relaxed, at the side of their body. This is not a re-calibration of the system, rather a re-set of the force outputs to bring all the force values back to zero. Prior to each pair of swings taken, the golfers' grip joint angles were recorded. For this, the participant was asked to stand in their 'ready position', being the stance that they would be in prior to making a swing. The evaluator stood in front of the participant and positioned the video camera perpendicular to the orientation of the joint markers. Upon study completion, the sensors were removed, and the data was extracted from the system.

3.2.3 Data Processing

3.2.3.1 Dartfish Movement Analysis Software

The data analysis process was similar to the analysis described in Chapter 2 section 2.2.3. Participants' static grip positions were recorded using a single standard video camera (GoPro Hero 5) while gripping each of the 12 standard and 'arthritic' designed golf grips. The 12 individual videos taken were imported into the Dartfish ProSuite 9.0 video software. The angle-tracking tool was used to measure the joint angles of the thumb MCP and CMC, and the index MCP and PIP. Measures were taken when the position of the thumb and index, were perpendicular to the camera view. An intra-rater reliability analysis was also conducted.

3.2.3.2 Pressure Profile Systems (PPS) Finger Tactile Pressure Sensors (FingerTPS)

The finger force data collected for each of the 12 grips and golf grip strength activities were extracted from the system to a .csv file. Time stamps for each swing were recorded manually by the evaluator during testing and inputted into an excel file. These time stamps were used to segment the extracted data. A code was created using MATLAB 2017b software (The MathWorks Inc., USA) to take the time stamp file and section the extracted force data. The program generated graphs of trials one and two for each of the12 golf grips and grip strength tests. Each graph depicted the thumb, index, middle, and ring finger force (N) variations, in terms of time (s) (samples of the graphs are shown in Appendix I1 and I2). A separate excel file was also generated, depicting the maximum forces in each finger, for each grip and grip strength test performed. Outliers were addressed by eliminating maximum individual finger force values above 100N and below 0N. This threshold was established by observing values from previous studies [57], [74], [75].

Each of the maximum force values of the thumb, index, middle, and ring finger were separately averaged for each activity conducted. The thumb, index, middle, and ring finger average maximum values were then summed for the regular and maximum golf grip strength activity, and for each golf grips tested to obtain an overall golf grip force. Each of the total maximum hand force values obtained for the 12 standard and 'arthritic' deigned golf grips for the healthy participants and participants with hand arthritis, were normalized to each group's maximum golf grip force. This demonstrated the percentage of grip force during a golf swing with respect to the maximum golf grip strength for the healthy participants and participants with hand arthritis.

3.2.4 Statistical Analysis

IBM SPSS Statistics Analysis software version 25, was used to evaluate the golf grip configuration and grip force data. To evaluate the variability in the force data between the healthy participants and participants with hand arthritis, a univariate ANOVA was conducted. This allowed for a comparison between the two groups to determine if any differences were present. To assess the variability between each finger segment across each of the 12 grips tests, a mixed repeated measures ANOVA (Analysis of Variance) was conducted. This analysis compares more than two measurements of the same participant group to show the interaction between the independent variables to the dependent variable (the grip configuration and force data). A post hoc power analysis ($1-\beta$ error probability) was calculated using the G*Power program [68] to determine if the type-1 (α) and type-2 (β) error probabilities were controlled for. Therefore, to determine if the sample size was sufficient in providing results that are comparable to the given population, the acceptable power level was set to $1-\beta>0.8$ [69]. A Bland-Altman or difference plot method, paired with a linear regression, was used to indicate the overall reliability (within 95%) of the variance of marker placement, and the joint angle measures, within the single evaluator (intra-rater reliability). Each of these tests were used for both the golf grip configuration and golf grip force data sets. Statistical significance was considered when $P<0.05$.

3.2.5 Assumptions

The assumptions for this study were:

1. The averaged and summed forces obtained for the thumb, index, middle, and ring fingers were considered to represent the total golf grip force of the bottom gripping hand.

2. Each participant's swing pattern was assumed to be consistent throughout the test.

3. The FingerTPS sensors were assumed to have singularly measured the linear force exerted by the thumb, index, middle, and ring finger onto each grip design.

3.3 Results

3.3.1 Golf Grip Configuration Results

Using the Grip Configuration Model, a significant limitation was seen in the participants with hand arthritis compared to the healthy participants. The largest weakness between the two groups was 15.8% (H: 35% and A: 50.8%) in the soft firmness (CP2 Pro), undersized grip. No difference was observed across each of the 12 grips, for either the healthy participants (P=1.0) or participants with hand arthritis (P=1.0). The grip configuration results are shown below in Figure 26 and Table 7.

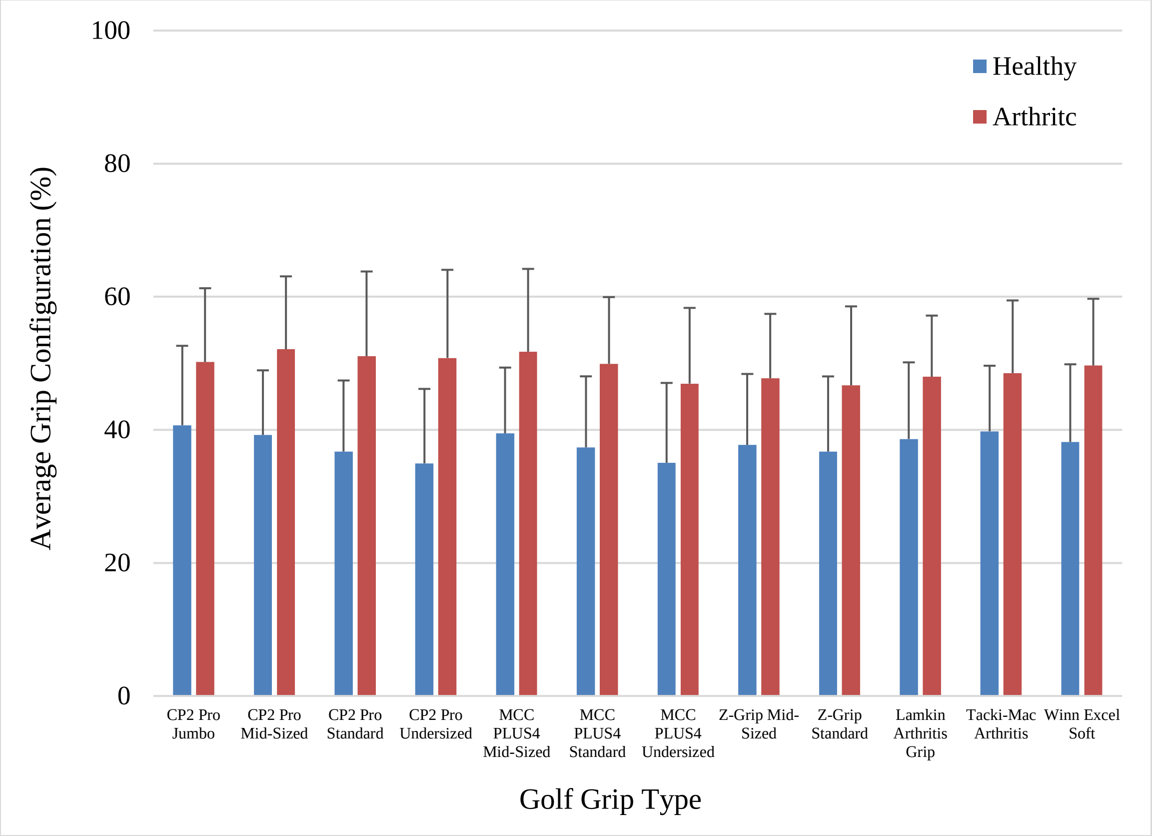


Figure 26: The grip configuration percentages for each of the 12 standard and ‘arthritic’ designed golf grips for both the healthy participants and participants with hand arthritis (n=10 healthy participants: n=8 participants with hand arthritis). Positive standard deviation (SD) bars are also included.

Table 7: The grip configuration percentage values for the healthy participants and participants with hand arthritis. The upper and lower 95% confidence intervals (CI) are presented for each heath status, the positive standard deviations (SD), and the overall percentage difference between the two groups (n=10 healthy participants: n=8 participants with hand arthritis).

Golf Grip Type	Healthy (%)	Positive SD (%)	Healthy Upper and Lower CI (%)		Arthritis (%)	Positive SD (%)	Arthritis Upper and Lower CI (%)	
CP2 Pro Jumbo	40.7	11.9	45.9	35.5	50.2	10.8	55.1	45.3
CP2 Pro Mid-Sized	39.2	9.7	43.5	35.0	52.1	11.0	56.9	47.3
CP2 Pro Standard	36.7	10.7	41.4	32.0	51.1	12.7	56.6	45.5
CP2 Pro Undersized	35.0	11.2	39.9	30.1	50.8	13.3	56.6	45.0
MCC PLUS4 Mid-Sized	39.5	9.9	43.8	35.1	51.8	12.4	57.2	46.3
MCC PLUS4 Standard	37.34	11.0	42.0	32.7	49.9	10.0	54.3	45.5
MCC PLUS4 Undersized	35.1	10.7	40.3	29.8	47.0	11.4	51.9	42.0
Z-Grip Mid-Sized	37.7	10.7	42.4	33.0	47.8	9.7	52.0	43.5
Z-Grip Standard	36.7	11.3	41.7	31.8	46.7	11.9	51.9	41.5
Lamkin Arthritis Grip	38.6	11.5	43.7	33.6	48.0	9.2	52.0	43.9
Tacki-Mac Arthritis Serrated Standard Grip	39.78	9.9	44.1	35.5	48.5	10.9	53.3	43.7
Winn Excel Soft Oversized Grip	38.2	11.7	43.3	33.0	49.7	10.0	54.1	45.3

3.3.2 Golf Grip Force Results

The 17 healthy golfers' average regular golf grip, and maximum golf grip strength capabilities were 71.8N, and 138.4N, respectively. The 10 golfers with hand arthritis averaged 47.5N for their regular golf grip strength, and 61.7N for maximum golf grip strength. This demonstrated a significant weakness of 45% (P=0.02) in the individuals with hand arthritis maximum golf grip strength capabilities. In evaluating the groups independently, the healthy participants showed a significant difference (P<0.001) between the regular and maximum grip strength activities. However, the individuals with hand arthritis did not (P=0.5). These results are demonstrated below in Figure 27.

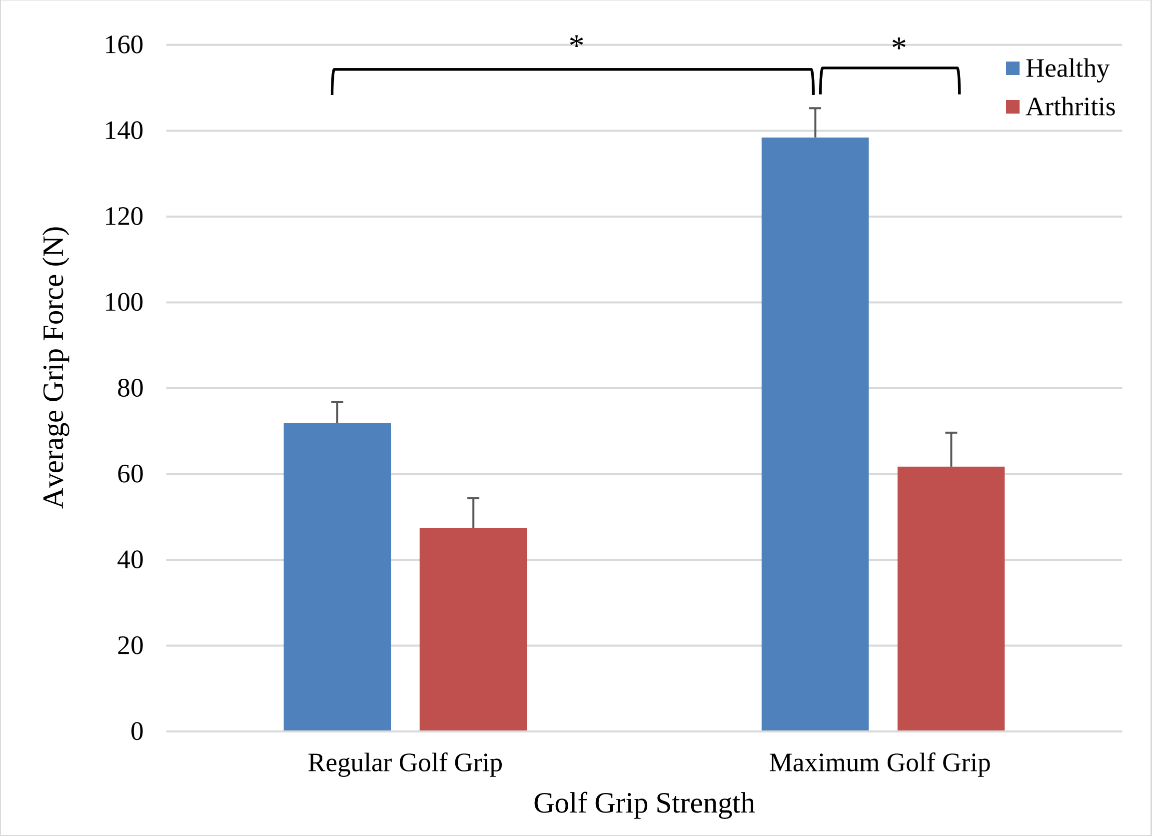


Figure 27: The average golf grip forces for regular and maximum golf grip strength are displayed for the healthy participants and participants with hand arthritis. Positive standard deviation (SD) bars and significance indications (*) are also included (n=17 healthy participants: n=10 participants with hand arthritis).

Compared to the healthy participants, it was observed that individuals with hand arthritis had a lower golf grip force across all 12 grips tested. The only grip which did not follow this trend was the standard diameter, medium firmness (MCC PLUS4) grip. This grip averaged a force of 94.2N, compared to the healthy participants' result of 87.3N. However, there was no statistical difference between the healthy participants and participants with hand arthritis in the thumb (P=1.0), index (P=1.0), middle (P=1.0), and ring (P=1.0) finger across each of the 12 golf grips tested. Each of the test groups were also independently evaluated across each of the 12 golf grips with no differences in the thumb, index, middle, or ring finger force outputs healthy participants thumb (P=0.3), index (P=0.4), middle (P=0.4), and ring (P=0.4) (Figure 28), or participants with hand arthritis thumb (P=0.3), index (P=0.3), middle (P=0.3), and ring (P=0.3) (Figure 29).

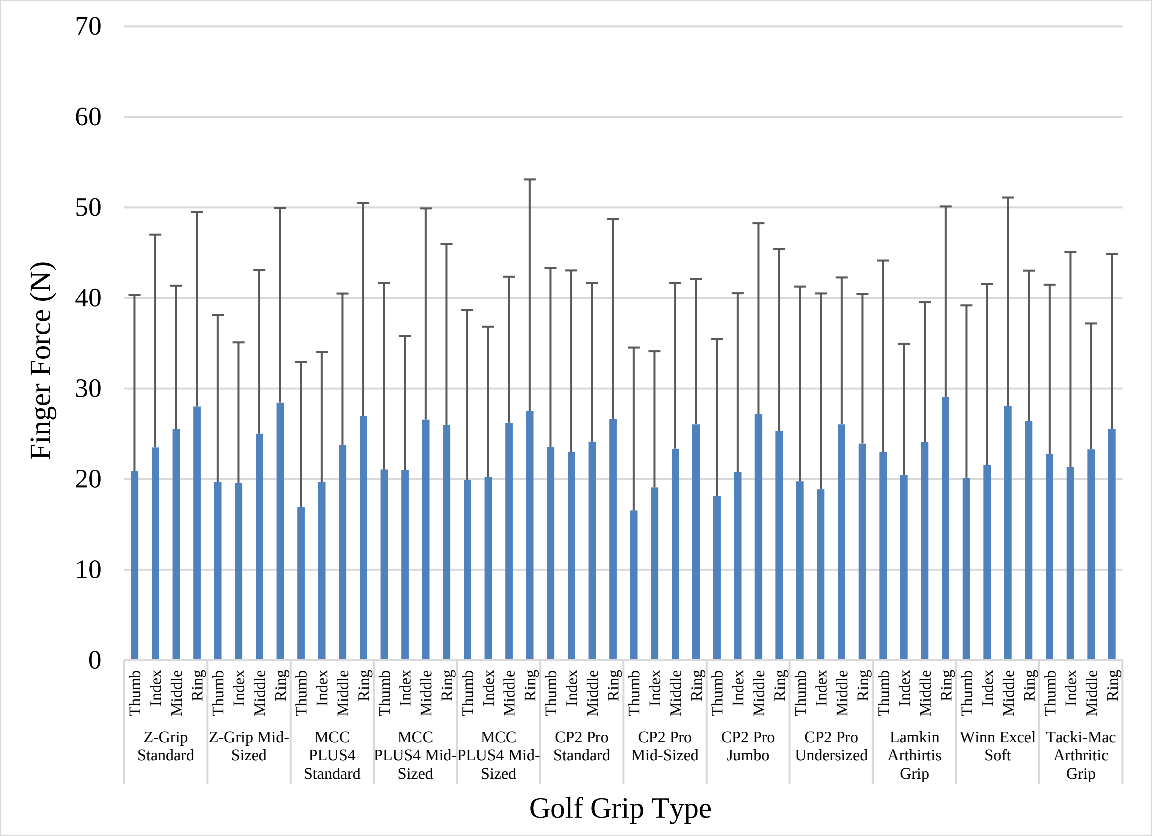


Figure 28: The healthy participant's golf grip force values exerted by the thumb, index, middle, and ring fingers when swinging with each of the 12 golf grips tested. The positive standard deviation (SD) bars are presented (thumb n=16, index n=15, middle n=17, ring n=14).

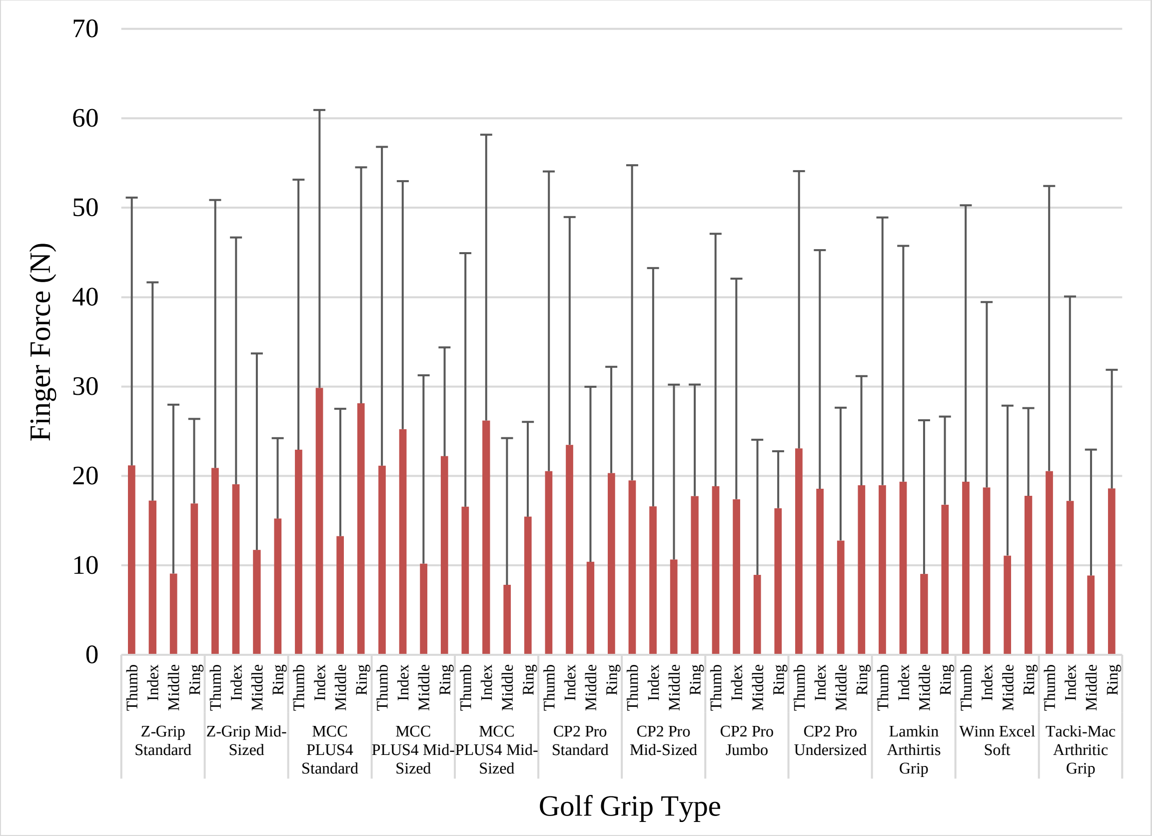


Figure 29: The participant's with hand arthritis golf grip force values exerted by the thumb, index, middle, and ring fingers when swinging with each of the 12 golf grips tested. The positive standard deviation (SD) bars are presented (thumb n=9, index n=10, middle n=9, ring n=8).

The healthy participants exhibited lower overall grip force values when swinging each of the 12 grips compared to their average maximum golf grip strength measure. For the individuals with hand arthritis, the average grip forces generated in 11 out of the 12 grips, exhibited higher values than their maximum golf grip strength capabilities. The soft firmness (CP2 Pro), jumbo sized grip was the only grip which generated a lower force than the maximum golf grip strength. However, this difference was only 0.11N. Figure 30 below, shows the average overall grip force values, across each of the 12 grips tested, normalized to each group's maximum golf grip strength capabilities.

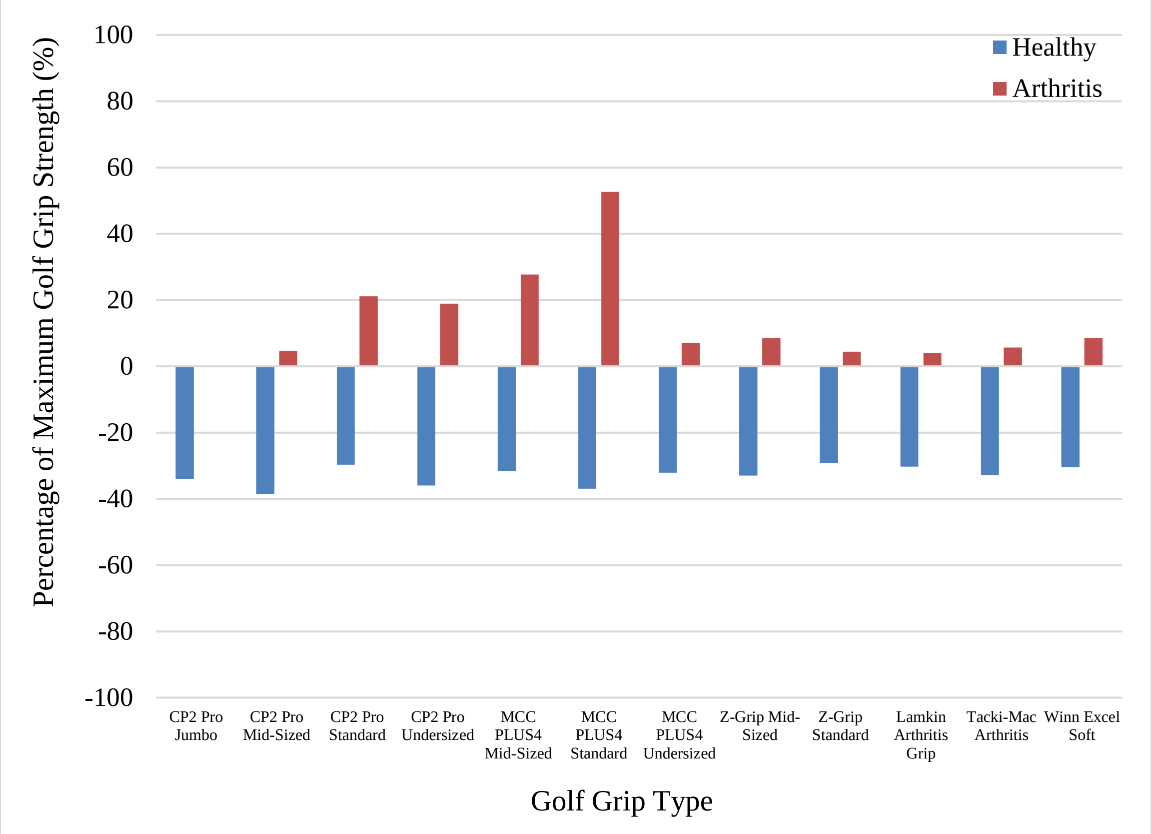


Figure 30: The average grip force for each of the 12 grips, normalized to their maximum golf grip strength for both the healthy participants and participants with hand arthritis (n=17 healthy participants: n=10 participants with hand arthritis).

In the healthy participants, the highest grip force output was 98.0N in the standard diameter, Z-Grip (hard firmness). The lowest grip force output was 85.0N in the mid-sized, CP2 Pro (soft firmness) grip. In the group with hand arthritis, the highest grip force output was in the standard diameter, MCC PLUS4 (medium firmness) grip, being 94.2N. The lowest grip force output was in the jumbo diameter, CP2 Pro (soft firmness) grip, being 61.6N. The two groups were independently evaluated to identify interactions in grip geometry (diameter) and material. The healthy participants, and participants with hand arthritis, demonstrated no differences across the four different diameter size grips. The soft, medium, and hard firmness material designs, showed no differences in the grip force outputs in either the healthy participants, or participants with hand arthritis. The average grip forces for the healthy participants and participants with hand arthritis, across each of the 12 grips are shown in Table 8 and Table 9 below.

Table 8: The average grip forces for each of the 12 grips and the golf grip strength values for the healthy participants, organized from highest to lowest force output. The upper and lower 95% confidence intervals (CI), and the positive standard deviations (SD) are also presented (n=17).

Golf Grip Type and Grip Strength Test	Healthy Participants Force Values (N)	Positive SD (N)	Upper and Lower CI (N)	
Maximum Golf Grip Strength	138.4	6.8	141.3	135.6
Z-Grip Standard	98.0	3.0	99.2	96.7
CP2 Pro Standard	97.3	1.6	98.0	96.7
Lamkin Arthritis Grip	96.6	3.6	98.1	95.1
Winn Excel Soft	96.2	3.8	97.8	94.6
MCC PLUS4 Mid-Sized	94.6	3.0	95.9	93.3
MCC PLUS4 Undersized	93.9	4.0	95.6	92.3
Tacki-Mac Arthritis Serrated Standard	92.9	1.8	93.6	92.1
Z-Grip Mid-Sized	92.8	4.3	94.6	90.9
CP2 Pro Jumbo	91.4	4.1	93.2	89.7
CP2 Pro Undersized	88.6	3.4	90.1	87.2
MCC PLUS4 Standard	87.3	4.4	89.2	85.5
CP2 Pro Mid-Sized	85.0	4.3	86.9	83.2
Regular Golf Grip Strength	71.8	69.7	73.9	69.7

Table 9: The average grip forces for each of the 12 grips and the golf grip strength values for the individuals with hand arthritis, organized from highest to lowest force output. The upper and lower 95% confidence interval (CI), and the positive standard deviations (SD) are also presented (n=10).

Golf Grip Type and Grip Strength Test	Hand Arthritis Group Force Values (N)	Positive SD (N)	Upper and Lower CI (N)	
MCC PLUS4 Standard	94.2	7.5	98.5	89.9
MCC PLUS4 Mid-Sized	78.8	6.6	82.6	75.0
CP2 Pro Standard	74.8	5.7	78.1	71.4
CP2 Pro Undersized	73.4	4.2	75.8	70.9
Z-Grip Mid-Sized	67.0	4.1	69.3	64.6
Winn Excel Soft	67.0	3.8	69.2	64.7
MCC PLUS4 Undersized	66.0	7.5	70.4	61.7
Tacki-Mac Arthritis Serrated Standard	65.2	5.2	68.2	62.2
CP2 Pro Mid-Sized	64.5	3.8	66.8	62.3
Z-Grip Standard	64.5	5.1	67.4	61.5
Lamkin Arthritis Grip	64.2	4.8	67.0	61.4
Maximum Golf Grip Strength	61.7	7.9	66.3	57.1
CP2 Pro Jumbo	61.6	4.4	64.2	59.0
Regular Golf Grip Strength	47.5	6.9	51.5	43.5

3.3.3 Reliability Analysis

In using the G*Power program, this study design was calculated for both the Grip Configuration and grip force aspects of this study. The power for the grip configuration was 1-β=0.61, therefore there was not sufficient power (1-β<0.8) in the component of the study. For the regular golf grip strength and (1-β=1.0) and maximum golf grip strength (1-β=) evaluation, they did show to have sufficient power (1-β>0.8). This concludes that the results for the golf grip force measures are an appropriate representation of the population, however the golf Grip Configuration evaluation needed to have a larger sample size. With the FingerTPS system being capacitive sensors, high shear forces experienced during the golf swing were of concern. The latex finger cots placed underneath and over top of the sensors, assisted in dissipating the shear forces, and prevented the sensors from delaminating. Proper fit of the finger sleeve sensors was monitored, as ill-fitting sensors caused miss-readings in the data. Miss-readings were represented by negative force values, indicating movement of the bottom plate of the sensor (the plate closest to the skin). A latex finger cot placed over top of each sensor, helped ensure that the sensors were "snug" to the participant's fingers without restricting movements. Even with this solution, several individual finger force data points were removed (below 0N and above 100N). This resulted in the statistical power (1-β) of the thumb (1-β=0.08), index (1-β=0.1), middle (1-β=0.09), and ring (1-β=0.1) finger force values being insufficient. Therefore, statistical differences were unable to be calculated between each of the 12 golf grips tested.

An inter-rater reliability analysis was conducted to evaluate the accuracy of marker placement, and joint angle evaluation of each golfers' grip configuration. A professional golfer (handicap 0) performed 11 gripping actions using a medium firmness (MCC PLUS4), standard diameter grip. A Bland-Altman or difference plot method, paired with a linear regression analysis demonstrated no proportional bias (P=0.4) within the single evaluator as each of the data points were within the 95% limit bounds (Figure 31). Therefore, this legitimizes the joint angle measurement results obtained in this Chapter.

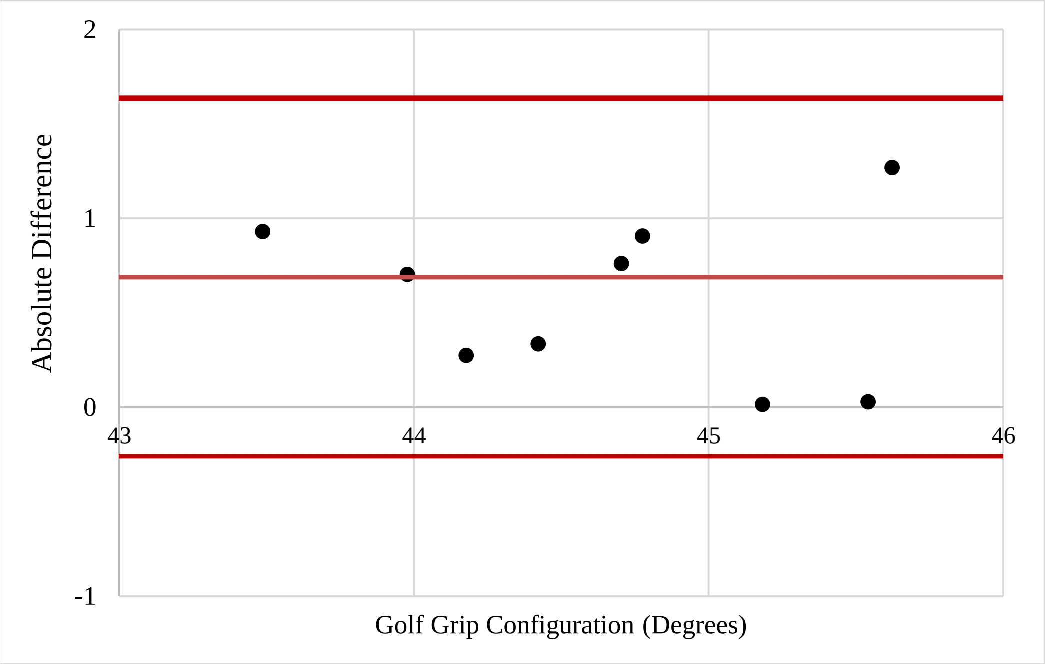


Figure 31: Bland-Altman analysis for the golf grip configuration inter-rater reliability evaluation with the upper and lower 95% confidence intervals represented by the horizontal red lines and the total mean represented by the horizontal blue line.

3.4 Discussion

In this study, the FingerTPS System was shown to be an appropriate non-invasive, wireless measurement tool to examine applied finger forces when swinging golf clubs with various golf grips. The results of this study showed a greater than 45% weakness in the maximum golf grip strength capabilities of golfers with hand arthritis. Broker *et al.* employed a flexible pressure array, attached to golfers' own clubs, discovering that total grip forces, peaked at nearly 73% of one's maximal grip force capability [75]. In this current study, a peak of nearly 71% was observed in the healthy group. The second major finding of this study was that for the individuals with hand arthritis, 11 out of the 12 grips tested averaged higher force outputs than their maximum golf grip strength. This is extremely concerning as an increase in the forces experienced by the hands, can cause further damage to the joint structure, pain, and progression of the disease. The lowest grip force output was observed when using the jumbo diameter, CP2 Pro (soft firmness) grip, being 61.6N. This particular design felt "good in (their) hands" due to the pliable material design and tacky feel of the soft firmness grips. It was also observed that the MCC PLUS4 (medium firmness), standard diameter grip, exhibited a 6.8N higher force output in the group with hand arthritis than the healthy group. A medium firmness, standard diameter golf grip, is generally the grip design that is placed on every club when initially purchased. A study conducted in 2013 (n=24), evaluated 5 different diameter sized grips. It was found that players who use a standard-sized grip, only had a 50% chance of a static grip measurement system matching to that grip size [86]. Many players do not re-grip their clubs to appropriately fit their needs, due to the added expense and lack of knowledge about the different golf grip designs. Our online survey (online survey questions and data shown in Appendix F) showed that for 60% (31/52 participants) of the sample (consisting of individuals with and without hand arthritis), the medium firmness grip material was the most commonly used, with 75% (40/53 participants) using the standard diameter size grips on their clubs. These findings suggest that standard and 'arthritic' designed golf grips may cause excessive force in golfer's with arthritis hands. Therefore there is no clear indication that 'arthritic' designed golf grips are beneficial to golfers with hand arthritis.

Evaluating golfer's grip ROM is important as it is one of the major limitations seen in individuals with hand arthritis. By employing the Grip Configuration Model, golfer's grip ROM were quantified when gripping the 12 standard, and ‘arthritic’ designed golf grips. This allowed for the detection of differences between individuals with and without hand arthritis. In Chapter 2, it was found that individuals with hand arthritis had a 17.2% limitation in their maximum flexion capabilities. The largest limitation seen when gripping a golf club was 15.8% in the soft firmness (CP2 Pro), undersized grip. Therefore, this limited grip ROM in individuals with hand arthritis is not only seen during the performance of a simple ROM action but also during recreational activities. However, in evaluating each group individually, no differences were observed in the grip configuration measures between each of the 12 golf grip designs. Grip size (circumference) difference between the largest and smallest grip in this study was approximately 1.9mm (measured at the bottom of the grip, closest to the head of the club). This may not be a sufficient geometry variation to demonstrate a significant effect on players’ golf grip ROM. However, a trend was observed with the larger diameter grips having larger grip configurations, and smaller diameter grips having smaller grip configurations. Through independently assessing the joint angles across each of the 12 grips, the thumb MCP joint was the only joint where the participants with hand arthritis had a more flexed position than that of the healthy participants. This shows the potential overexertion of a single joint to compensate for the lacking ROM capabilities, and possible pain experienced in the other joints of the hand. Current literature, discussed in Chapter 1 section 1.1.3, has specifically evaluated the grip ROM capabilities in each joint of the hand. Though valuable, this information is complex, and difficult for clinicians to easily assess when evaluating patients with musculoskeletal diseases, such as arthritis. The development of the Grip Configuration Model demonstrated in Chapter 2 section 2.2.4, gives a simple, single measure that is easy for researchers and clinicians to evaluate and patients to comprehend.

Several studies have evaluated the full body mechanics of the golf swing using optical based tracking system. Chu *et al.* investigated the performance variables important to ball velocity during a shot with a driver [52]. The kinematic data of the golf swing was collected using eight, high-speed cameras, controlled by the Peak Motus System (Peak Performance Technologies, Inc., Englewood, CO) [52]. Carson *et al.* examined the control levels between a practise swing and a real golf swing [87]. The MVN Studio software (Xsens Technologies B.V., The Netherlands) was used to collect the kinematic movements

[87]. The data was analysed with Visual3D v4.89.0 software (C-Motion Inc., Germantown, MD, USA) using a six DOF modeling [87]. The overall results showed differences in the effects between participants' performance. This reflects the variability in each golfer's swing technique, with strategies to improve performance needing to be tailored to each performer's biomechanical abilities [87]. These studies have provided a better understanding of the kinematic movements experienced during the less than three second golf swing. However, previous literature has not investigated the specific kinematic movement patterns of the hands and wrist extension during the golf swing. In this current study, each golfer's grip configuration was only evaluated during their static, "ready" positions. However, the goal of this study was to determine if the grip ROM differences between the healthy golfers and golfers with hand arthritis was translated to the recreational activities of golf. This was observed across each of the 12 standard and 'arthritic' designed golf grips tested but not statistically proven as the participants with hand arthritis had a weakened grip force in a majority of the grips tested compared to the healthy participants.

With 'arthritic' designed golf grips only recently having been developed, to the best of our knowledge, no comprehensive examinations have been conducted on these 'arthritic' designed grips. However, they are marketed as such. In comparing the three 'arthritic' designed grips to the standard grip designs tested, no statistically significant reduction in grip force outputs were found. In the healthy sample, the Lamkin Arthritis Grip and the Winn Excel Soft Grip were on the higher end of the grip force output spectrum (results seen above in Table 8). For the individuals with hand arthritis, the Lamkin Arthritis Grip exhibited the second lowest, average grip force output. Unlike the soft firmness (CP2), jumbo grip, it averaged a 2.5N larger force output than the maximum golf grip strength for the individuals with hand arthritis. There was also little variation in the grip configurations, for both the healthy participants, and participants with hand arthritis with the general observation of the participants with hand arthritis being in a more extended position. The Tacki-Mac Arthritic grip demonstrated the smallest grip configuration difference of 8.7% (H: 39.8% and A: 48.5%), between the healthy participants and participants with hand arthritis. The Tacki-Mac grip has the same diameter as that of the soft firmness (CP2 Pro), standard diameter grip. However, the soft firmness (CP2 Pro), standard diameter grip, exhibited the second largest difference (14.3%) in the grip configuration results. This demonstrates that the participants with hand arthritis are gripping the Tacki-Mac ‘arthritis’ designed grip in a tighter fashion (more flexed grip position). With the goal of joint protection assistive devices to reduce ‘tight gripping’ when executing activities [24], the Tacki-Mac Arthritic grip does not accomplish this requirement.

Previous golf biomechanics studies, have consisted of small sample sizes, only having evaluated men, and using large or interfering measurement tools. This current study addresses these concerns having a sample size of 27, evaluating both male and female participants in both groups, and using minimally invasive measurement tools (Dartfish Movement Analysis software and FingerTPS system). The Dartfish Movement Analysis software is a 2D software. In comparison to other forms of optical tracking technology, which produced similar results for simple hand ROM tracking tests, Dartfish provides a less invasive and inexpensive technique. Paired with the simple, single grip configuration measurement system, it allowed for a wider application than what is currently presented in the literature. However, in being a simple 2D measurement system, and the biomechanical movements of the hand being complex and 3D, it posed several issues which were discussed in Chapter 2 section 2.4. The FingerTPS system was an appropriate, wireless measurement device for this current study as the objective was to evaluate the forces at the fingertips since hand arthritis more commonly affects the distal joints. Measuring the forces at the dominant location where hand arthritis occurs, provided applicable data to the research question being asked. Strain gauge fingernail sensors were initially prototyped for use in this current study. The strain gauge sensors were mounted onto acrylic substrates, with a curved feature. This curved feature, varied in degrees of curvature to closely match the shape of the nail to be placed on. When a force was applied to the distal palmar finger pad, the nail would deform, therefore causing the strain gauge to bend with the nail. The strain measured was then translated to a force in Newtons. The ability to measure the forces at the fingertips without interfering with the hand/grip interface is a major benefit. However, repeatability of sensor performance and construction, as well as accuracy of the measurements taken were of major concern. The system was also bulky, and required a small backpack style harness worn during testing. The FingerTPS System greatly improved upon these limitations. The FingerTPS system is encompassed into a minimally invasive, micro spandex finger cot [83]. Having a sampling frequency of 50Hz makes it an appropriate choice for measuring the variable grip force measures during the less than three second time frame of a golf swing.

As discussed in Chapter 1 section 1.1.4, the thumb generates smaller forces than the fingers when grasping cylindrical objects less then 30mm in diameter using a power gripping style but generated larger forces when grasping cylinders larger than 50mm [20]. The average top and bottom diameter of a standard golf grip is 2.7mm and 1.9mm (referenced from the MCC PLUS4 standard diameter grip designed by Golf Pride, Appendix C2.). The average finger force results of the thumb, index, middle, and ring finger for the healthy participants and participants with hand arthritis when swinging with the MCC PLUS4 standard diameter grip were evaluated (shown in Appendix I4). The results for the healthy group demonstrated that the thumb and index finger forces were the lowest compared to the middle and ring finger. However, in the group with hand arthritis, the index finger generated the highest average finger force and the thumb had the second lowest to that of the middle finger average force. This difference between the two groups depict the individual finger force variability in golfers with hand arthritis. Also, in the bottom gripping hand of a golfer’s grip, the thumb and index fingers exhibit a precision gripping style. In the study above, Tsuyoshi *et al.* evaluated the finger forces when using a power gripping style. The contrast between these two studies demonstrates the differences in the two gripping styles and how they influence the magnitude of force generated by the individual finger segments and thumb. This illustrates that the shape of the object and the gripping style executed are both influential components on the finger and thumb forces generated when participating in recreational activities and various ADL.

3.4.1 Strengths and Limitations

This study is not without limitations. The sample size of this study was not powered for stratification of results based on additional factors such as age and sex. In future study structures, factors such as age, sex, and other disorders or injuries of the body/co-morbidities should be systematically examined. Vibration due to the impact of the club with the artificial turf/ball was also not specifically examined in this study. Potential vibrations may have been detected in the sensors when the club came in contact with the ball. This vibration would have resulted in an inflation of the forces experienced at the fingertips of the thumb, index, middle and ring finger, and therefore the overall golf grip force calculations. This could have also caused the possible elimination of data points if the maximum outputted force was greater than 100N.

The FingerTPS system was designed using capacitive sensors. As these capacitive designed sensors are only able to measure linear forces, shear forces result in output errors and damages the sensors. This issue was controlled for with the latex finger cots, as they provided a snug enclosure of the sensors on each finger tested. This allowed for minimal transverse movements of the sensors during the golf swing. Every participant in the current study wore the latex finger cots over top of the sensors. An analysis of the sensors' performance with and without the top layer of latex was conducted. A professional golfer (handicap 0) performed 20 swings with each procedure, using a medium firmness (MCC PLUS4), standard diameter grip. The results demonstrated no statistical difference in the thumb (P=0.6), index (P=0.07), and ring (P=0.7) finger (results shown in Appendix I3). However, there was a statistical difference seen in the middle finger force results (P=0.01). This difference could have been due the small sample size or malfunction of the FingerTPS sensor as without the layers of latex finger cots, the sensors are in direct contact with the grip potentially increasing the shear force impact experienced by the sensors.

The FingerTPS system also had a video camera which could be used to match the movements of the participants with the finger force variations. However, when using the video camera to record each participant's swing, only half of the test videos would properly run. Several efforts to solve this issue were explored such as running the program on a computer with larger memory, conducting the test within a shorter period of time, and using less finger sensors. Each of these potential solutions however, did not result in consistent outputs with only part of each participant's test recorded and paired with the finger force data. Therefore, the video evaluations of each player's swing with the sensor output was excluded from this study.

Another limitation was in the varying golf gripping styles, demonstrated by each participant. The three main gripping styles used by golfers, previously described in Chapter 1 section 1.5.4, are the overlapping, interlocking, and baseball (10 finger). In this current study, out of the sample of 27 participants, 41% used the overlapping style, 41% used the interlocking, and 18% used the baseball/ten finger gripping style. Our online survey results (n=54) showed similar distributions in gripping style preference with 57% using overlapping, 32% the interlocking, and 11% the baseball/ten finger style (online survey questions and data shown in Appendix F). This demonstrates that the sample in this current study is similar to the general golfing population. These gripping style variations did not affect the results of the grip configuration values, as in each of these styles of grips, the bottom gripping hand thumb and index finger are in the same orientation. For the finger forces exerted onto each club, only the thumb, index, middle, and ring fingers were evaluated for each participant's bottom gripping hand. With each of these gripping styles, the variations only involve the small finger of the bottom gripping hand and the index finger of the top gripping hand. Therefore, there would be no interference with the golf grip configurations observed. To determine if this conclusion held true for the grip force output at the fingertips, a professional golfer (handicap 0), completed 10 swings, executing each gripping style using a medium firmness (MCC PLUS4), standard diameter grip. In conducting a univariate analysis (ANOVA), there was a statistical difference between the three different gripping styles ($P<0.001$, $1-\beta=1.0$). However, the main variability came from the baseball gripping style with the interlocking and overlapping style exhibiting similar results. As stated previously, only 18% of the current study's sample used the baseball gripping style. Therefore, only a small portion of the data could have an additional impacting factor. The power generated by the overlapping and baseball gripping styles was also studied by Noble *et al.* [88]. A ballistic pendulum was used to measure the power generated by 18 male students using each gripping style with no differences observed [88]. Therefore, in observing these variabilities in this current study and previous studies, this warns further investigation of this component.

Komi *et al.* demonstrated that the forces at the palm of the right hand (bottom hand for a right handed player) during the swing, were larger than that in the fingers and thumb [57]. In this current study, the measures of the palm and finger phalangeal segments were eliminated due to the fact that it would have required additional sensors and therefore increased the number of components involved in the system. The FingerTPS system does have sensors for the phalangeal segments and a single point sensor for the palm. However, increasing the number of components at the hand/golf grip would increase the material bulk between the hand/golf grip interface. The signal condition wrist assembly also only consists of 6 ports which would not allow for every fingertip, phalange, and the palm to be simultaneously measured.

The golf equipment used in this study consisted of 12 mid-iron (7-iron) clubs. As discussed in Chapter 1 section 1.5, approximately 31% of the shots taken during a round of golf are with irons. Seeing as this represents a majority of the shots taken during a game of golf, it validates the use of 7-irons in this study. Also stated in Chapter 1 section 1.5.3, a majority of the golfing population wear gloves. For this current study participants did not wear a golf glove(s). A reason for excluding the use of a golf glove was to eliminate the possible interference of the glove with the FingerTPS sensors. This ensured that the results would singularly demonstrate the interaction between the hands and the golf grip itself by eliminating excess material bulk. Other issues with using a glove were that a new, appropriately sized glove would be needed for each participant. A new glove is stiff and restrictive and would need to be “broken in” to what feels natural to each player. The glove potentially used may also not have been the brand or material design that each participant would have been comfortable with. All of these factors increase the variability of each player’s natural gripping style. By simply excluding the use of a glove, these influential factors are eliminated.

3.5 Conclusion

The main purpose of this study was to observe the influences that different golf grip designs have on the grip ROM and force in individuals with and without hand arthritis. The hypotheses demonstrated in Chapter 1 were: larger diameter golf grips will result in a larger golf grip configuration (less flexion in the fingers), where the smaller diameter golf grips will result in a smaller (more flexed) grip configurations, in golfers with and without hand arthritis (Hypothesis 2), and the larger diameter, softer firmness golf grips will reduce the overall finger forces in both individuals with and without hand arthritis (Hypothesis 3). Results of this study concluded that differences were seen in individuals with hand arthritis for their golf grip ROM and force capabilities. This concluded that these limitations in the main functions of the hand caused by hand arthritis, are translated to the recreational activities of golf. It was observed that the larger diameter (jumbo and mid-sized), softer firmness (CP2 Pro) grips, exhibited the lowest grip forces and the largest grip configurations (less flexed position) in both groups tested. Another major finding of this study was specifically seen in the group with hand arthritis. Eleven (11) out of the 12 grips tested, averaged higher grip force outputs than their maximum golf grip strength. This is an alarming fact as in the healthy population this was the opposite outcome. These findings demonstrated that there is no clear indication that the ‘arthritic’ designed golf grips are appropriately designed for players with hand arthritis. This observation indicates the evidential need to progress further in this area of research, to discover solutions to this occurrence.

Few previous scientific studies and technologies have been designed to discreetly measure golf grip ROM and force. These studies consist of outdated results and small data sets. This has resulted in a limited understanding and background knowledge as to the physical occurrences happening at the hand/golf grip interface. This current study used the non-invasive FingerTPS system, to measure the individual finger forces (summed to demonstrate the total grip force), and a simplified kinematic measurement scale (Grip Configuration Model) and tool (Dartfish Movement Analysis Software) to evaluate the grip ROM. In contributing the first evidence based study, further evaluation into the effects that various types of golf grips have on the hands, would be beneficial.

Chapter 4 – Conclusion

4 Overview

The feasibility studies presented in this thesis looked to assess the practicality of employing the Dartfish Movement Analysis Software and the FingerTPS system. This was done to measure the hand movements (ROM) and forces when conducting activities of daily living (ADL), and when swinging a golf club with various golf grip designs. The main objective of this thesis was to determine which golf grip design reduced the overall grip force in golfers with and without hand arthritis when swinging a golf club. This chapter reviews the objectives and hypotheses outlined in Chapter 1 section 1.7, summarizes the work that was undertaken to test these hypotheses and fulfil these objectives, and discuss the strengths and limitations of this work. Finally, future research projects are outlined.

4.1 Summary

Arthritis is an incurable disease that affects 1 in 5 individuals over the age of 15, making it the number one cause of disability in Canada [21]. This ratio is magnified as age increases with 1 in 2 seniors over 65 having arthritis [21]. Hand arthritis, specifically osteoarthritis (OA), is one of the most common forms, causing disability, pain, stiffness, and a limited grip range of motion (ROM) and strength.

Assessing hand motion particularly of the finger segments, can be extremely difficult to conduct due to their small joints moving in multiple different orientations, all within a small space [59]. In the clinical and research domain, goniometers are used for ROM measurements of static hand positions. Simple dynamic movements of the hand have been evaluated using optoelectronic motion analysis, digital photographic images, instrumented gloves, optical tracking, and EM tracking tools [14]–[17], [33]–[36]. Chapter 2 described using a video-based approach which is an alternate grip measurement technique to evaluate functional joint movements during various function tasks. The Dartfish Movement Analysis Software was used to measure the joint angles of the thumb CMC and MCP, and the index MCP and PIP joints, in individuals with and without hand arthritis. These angle measures were used to develop the Grip Configuration Model to provide a single percentage value of participants' grip ROM (grip configuration). This model was used to evaluate kinematic changes of the hand (Objective 1a.) in individuals with and without hand arthritis while performing maximum flexion and maximum extension (Objective 1b.i.), and five activities of daily living (ADL) (Objective 1b.ii.). Chapter 2 findings demonstrated that patients with hand arthritis, specifically osteoarthritis, experience an instability in performing simple ROM tasks and ADL. This instability resulted in the spray bottle task demonstrating an average (pulling and releasing the trigger) limitation of roughly 13%, and a maximum flexion and maximum extension grip limitation of 17.2% and 12.7%, respectively. These findings demonstrate the translation of the functional limitations in range of motion in individuals with hand arthritis to activities of daily living (Hypothesis 1). The use of the Dartfish Movement Analysis Software was also compared against the digital EM tracking system and the commonly used manual goniometer, with a majority of the results demonstrating no differences. Simply quantifying this limitation in the grip motion of individuals with hand arthritis, allows clinicians to better evaluate and treat patients with hand arthritis. It also provides the patients with a better understanding of the characteristics of their specific limitations. We then used this knowledge to advance this area of research into the fields of sports biomechanics, specifically examining its effect on golf grips.

As discussed in Chapter 1 section 1.5, much of the current research surrounding golf has focused on full body mechanics to assist players and coaches with technique and injury assessment. However, there is a strong disconnect in the quantity and quality of research focusing on the area of golf and arthritis. With over 35% of the golfing population being over 50 years of age [71], and 70% of the population aged 50 years of age and older being affected by arthritis [72], it demonstrates the potential correlation between people who play golf and have arthritis. The only contact point between the player and the club is at the hand/golf grip interface. However, limited focus has been given to better understanding the interaction at this point of contact. Golf manufacturers have started to recognize this growing need for assistive devices to help the large population of golfers with hand arthritis continue to play. Specifically, Chapter 3 assessed three commercially available 'arthritic' golf grip designs for players with hand arthritis. The company Winn developed a larger diameter, softer firmness grip, and the companies Tacki-Mac and Lamkin have developed serrated textured design grips. The goal of these designs are to increase traction, and reduce the grip forces and vibrations at the hand/golf grip interface. The motivation behind these 'arthritic' designed golf grips stems from joint protection principles in avoiding positions that foster deformity, which involve tight, and high force gripping positions [24]. Standard designed golf grips defy these basic principles. However, comprehensive examinations have not been conducted on current 'arthritic' designed golf grips to provide quantitative results to support their claims. Therefore, Chapter 3 addressed these limitations by employing the FingerTPS system designed by Pressure Profile Systems. This measurement tool provides a non-invasive solution to evaluate the applied individual finger forces, and obtain a total grip force in golfers with and without hand arthritis when swinging a golf club (Objective 2).

In Chapter 3, a cohort of 27 participants (17 healthy participants: 10 participants with hand arthritis) were evaluated for their golf grip strength and ROM (10 healthy participants: 8 participants with hand arthritis). The Grip Configuration Model developed in Chapter 2 was used to assess the golfer's bottom gripping hand grip configuration of their thumb and index finger. This allowed for differences in the 12 different styles of grips to be evaluated between the individuals with and without hand arthritis (Objective 1b.iii). A customized protocol was developed for this study. Four sensors were placed on the participant's bottom gripping hand (the hand closer to the head of the club) thumb, index, middle, and ring finger. These measurements were compared across a variety of 12 standard (9) and 'arthritic' (3) designed golf grips to detect differences in golfers' with hand arthritis total grip force (Objective 3). A 45% weakened maximum golf grip strength was seen in the golfers with hand arthritis when compared to the golfers without hand arthritis. The smaller diameter, hard firmness grips, produced higher overall grip forces where the larger diameter, softer firmness grips generated lower overall grip forces. The Lamkin Arthritis Grip had the second lowest grip force for the golfers with hand arthritis. However, in the group without hand arthritis, the Lamkin serrated grip design generated the third highest grip forces. The Winn and Tacki-Mac 'arthritic' designed grips, generally had a neutral effect in both groups. However overall, golfers with hand arthritis use grip forces that exceed their maximum golf grip strength capabilities in order to swing a golf club. Therefore, there is no clear indication that ‘arthritic’ designed golf grips are beneficial to golfers with hand arthritis.

Grip strength and ROM are the two main functions of the hand. The findings of this research showed that the weakened grip strength and ROM in people with hand arthritis is translated to ADL and golf. It also shows no clear indication that ‘arthritic’ designed golf grips are beneficial to golfers with hand arthritis. From this, the first hypothesis of Chapter 3 was observed but not statistically proven. The larger diameter golf grips resulted in a larger golf grip configuration (less flexion in the fingers), where the smaller diameter grips resulted in a smaller (more flexed) grip configurations in golfers with and without hand arthritis (Hypothesis 2). However, this finding did not demonstrate a statistical difference. The other hypothesis of this study was also only observed. In both test groups, the larger diameter, softer firmness grips, were observed to be the design that exhibited the lowest forces in both groups tested (Hypothesis 3). However, there was no statistical difference between the grip forces across the 12 different golf grip designs for the two groups examined. From these types of evaluations, clinicians and manufactures can better assist individuals with hand arthritis by making recommendations and design improvements to golf grips in order to accomplish the goal of a reduced grip configuration and force for players.

4.2 Strengths and Limitations

It is recognized that the current studies conducted in Chapters 2 and 3 were not void of shortcomings. The video-based movement analysis software utilized in both studies (Dartfish), was a 2D based system. Being 2D, meant that it could only evaluate movements in a single plane of motion at one time. For the golf grip configuration measures conducted in Chapter 3, this was not a limitation as each golfer’s grip was taken during a static position. However, for the dynamic ADL evaluated in Chapter 2, this was not the case. Often, markers were hidden from the camera’s view making it difficult to measure the joint angles. This resulted in the exclusion of participants’ data. However, in Chapter 2 an assumption was stated that the movement patterns obtained by the joints of the thumb and index finger for the grip configuration model will be evaluated and assumed to represent 2D movements of flexion and extension (Chapter 2 section 2.2.7). It was also seen that during both studies, varying gripping styles were used by the participants. In Chapter 2 section 2.3, differences were seen during maximum flexion and the large jar twist top task. These variations were evaluated with no differences seen in the data. In Chapter 3 section 3.4.1, three basic gripping styles (interlocking, overlapping, and baseball grip) were assessed for variabilities in the grip configuration and force data, with differences seen in the baseball gripping style. However, only a small portion of the current study's sample used the baseball gripping style, therefore potentially minimizing the variability shown.

In utilizing the FingerTPS, capacitive designed measurement system in Chapter 3 to measure the finger forces during a golf swing, several concerns arose. Capacitive sensors are designed to measure linear forces. The high shear force environment at the hand/golf grip interface during a golf swing, presented concerns of sensor accuracy. Shear forces could cause damage to the system, therefore reducing measurement accuracy. This would result in extremely high force outputs or sensor failure. There was also the concern of ill-fitting sensors (finger sleeves). If the bottom plate of the sensor (closest to the pad of the finger) were to shift during a test, the resulting error would be a negative output. These issues were addressed by placing latex finger cots underneath and overtop of the finger sleeve sensors. This created a snug fit on the participants' fingers without being restrictive or creating extra material bulk. The latex finger cots also reduced the shear forces translated to the sensors during the golf swing.

Despite these limitations, significant strides were made through the employment of these tools and techniques to examine grip strength and ROM during ADL and a golf swing. Chapter 2's study protocol and the development of the Grip Configuration Model (Chapter 2 section 2.2.4), allowed for a more comprehensive evaluation of the gripping/grasping movement than presented in previous literature. The Dartfish Movement Analysis Software provided a less expensive, simpler technique, to produce similar results as previously conducted studies on the kinematics of the hand. Standardizing the camera positions, marker placements, and using the Grip Configuration Model, simple comprehensive comparisons between the maximum flexion/extension as well as for each of the 5 ADL were obtained. The anatomical landmark identification of the joints of the hand, between (inter-rater) and within the evaluators (intra-rater), was assessed and confirmed no variability. Both the Dartfish Movement Analysis Software and the

FingerTPS systems provided non-invasive measurement solutions to evaluating the small joints of the hand during static and dynamic activities. In the measurement tools being non-invasive, it allowed for participants to perform each activity as they naturally would. In Chapter 3, many strengths were identified in using the FingerTPS sensor system. Being a compact, wireless system, using Bluetooth technology, allowed the participants to move freely and not feel restricted when swinging a golf club. These benefits outweighed the limitations and provided useful, informative results, allowing for the main research questions of this study to be answered.

4.3 Future Direction

The results of this research have established a starting point for future studies. Employing the grip configuration and finger force measurement sensing protocol, other ADL, vocational, and recreational activities can be examined. It would also be valuable to implement a kinematic measurement system which could be worn for long periods of time. This would allow for a more detailed assessment of the hands biomechanics in day to day life, or during specific activities such as playing a round of golf. The team at IBM Research have designed a wearable fingernail sensor for behavioural and biomechanical monitoring [89]. The device uses a strain gauge sensor to measure single digit micron deflections of the fingernail [89]. Preliminary tests of the IBM developed fingernail sensors demonstrated accurate grip force measures for several ADL [89]. Implementing this technology into a study of similar structure as presented in this thesis, would provide an in depth evaluation of the individual finger forces during other activities.

An interview with the head teaching professional at Sunningdale Golf and Country Club in London, Ontario, compared the grips of a golf club to the steering wheel of a car. “The grips are what drives the rest of the swing…without a good grip there is no chance of having a good swing” [90]. This research is the first to study a variety of golf grip designs and the impact on golfers’ grip strength and ROM. In being a feasibility study, it paves the way for future studies. Other impacting factors such as vibration effects, different golf club designs, and artificial grass versus real grass, can be investigated. In regards to the vibration and hand force factors during a golf swing, these components can be simultaneously investigated to determine if one causes more pain or if one is more likely to cause musculoskeletal damage of the hand. Another factor that is suspected to play an important role and should be further investigated in future work is the golf grip material and diameter size. Investigating these factors would provide further detail into the design of golf grips in order to develop a better golf grip to reduce grip forces and ROM during a golf swing, which would benefit golfers with arthritis and possibly prevent or delay the onset of arthritis. Also in Chapter 3, one of the assumptions stated was that the performance measures in terms of each participant's swing pattern were assumed to be similar when swinging with each grip. This however may not the case. It is important to pair the biomechanical results of this study structure with performance results using tools such as TrackMan [73] to determine if a player's ball flight, club face angle, club speed, etc., are influenced by the different grip designs. In further investigating this area of research, it will provide players, clinicians, and manufacturers with a better understanding of the complex biomechanical interaction of the hand/golf grip interface.

Biomechanical modeling using 3D tools such as OpenSim, should also be further investigated to develop detailed and accurate evaluations of different components of the golf swing. Models of the golf swing have begun to be developed [91], [92]. However, these models lack the incorporation of experimental research data as conducted in this current study. Including this quantitative data would allow for the development of a realistic model of a golfer's swing. With the inclusion of this information into the models, inverse dynamics could be applied to obtain muscle, ligament, and joint contact forces in the hand, and other parts of the body throughout the golf swing. This type of modeling technique could also be applied specifically to the entire upper arm to simulate gripping and grasping tasks during ADL. Evaluating the internal biomechanics of healthy individuals and comparing it to individuals with hand arthritis, will expand the depth of knowledge in the field of upper limb biomechanics.

4.3.1 Future Golf Grip Design and Grip Measurement System

With the results of this current study and future studies conducted on this topic, a new ergonomic golf grip design and grip measurement system can be developed. This new design would be based on quantitative results to potentially: (1) reduce the grip force and vibration effects, (2) depending on hand size appropriately reduce the ROM required to grip the club, (3) assist individuals with hand arthritis properly grip the golf club, (4) reduce the risk of developing hand arthritis in golfers without hand arthritis, and (5) reduce the progression of hand arthritis in golfers with hand arthritis. Potential features of a new golf grip design would be a molded style grip that would consist of different ridges and materials. These different ridges would enable each individual finger and thumb segment to be positioned in an optimal grip configuration (flexion range). Pairing this with a combination of different materials at each finger and thumb segment, would provide the appropriate balance between a reduced grip configuration and force during a golf swing. This could be tailored to each player depending on their biomechanics, hand dimensions, environmental conditions, and if they have any hand injuries or diseases. Through the use of modern technology, a scan of a player's hand followed by a few simple questions would be taken. Combined with a basic biomechanical model and performance data of an individual's golf swing, a unique golf grip design model could be generated.

For the grips currently on the market, a new quantitative and qualitative based measurement system could be implemented. This measurement system would categorize grip diameter and material characteristics depending on a variety of factors such as hand length, age, sex, environment, hand perspiration level, and whether the player has any hand injuries or diseases. Based on these factors, the range of grips catalogued would be presented visually as a graph with the grip that would generate the highest grip force being the largest curve and the grip that would generate the lowest grip force being the lowest curve. This would also be done for the grip configuration of each grip. A software program would then combine these two results to present the optimal selection of grips which would both reduce the grip configuration and force during an individual player's golf swing.

4.4 Significance

The implementation of appropriately designed golf grips for different types of players is often neglected. A recent study concluded that 9 out of 10 golfers play with the wrong size golf grips [86]. Nearly 88% of the participants had standard-size grips on their own 5-irons [86]. When these players were measured for their appropriate grip size, less than 50% were measured for standard-sized grips.

In today's society, there is an increasingly aging population [93], with a majority of whom play golf and have hand arthritis [21], [71]. This has led to the clinical problem of standard golf grips not providing sufficient support to players with hand arthritis. Often, clinicians recommend golf as a low-impact activity for older individuals to maintain an active lifestyle and healthy joint function. However, if players are having a hard time gripping the clubs and without the proper tools in place to allow these players to be able to participate in the sport, this recommendation may not be beneficial. Using this study protocol and measurement systems in this thesis, a better understanding of the mechanics of arthritis and its relation to various daily living tools as well as golf grip designs can be obtained. The development of new adaptive tools, and strategies would assist individuals to be better able to independently preform various daily activities and not feel restricted by their disease or disability.

This research will benefit both the sports biomechanics and clinical fields. It will add context to the clinical field by providing a better understanding of the interactions experienced at the hand/golf grip interface. It will also demonstrate how individuals with musculoskeletal diseases such as hand arthritis, are impacted by varying golf grip designs. The findings of this research will allow clinicians to suggest specific golf grips that can reduce the grip forces when swinging. The sports biomechanics industry will benefit from this research as it is the first study to simultaneously evaluate 12 different golf grip designs, for both their impacts on golfers' grip strength and ROM. This research focused on one of the most important components of the golf swing being the hand/golf grip interface. Results provided a detailed evaluation of the biomechanical components of a golfer's grip, and the design of the golf grips themselves. However, research in this areas is extremely lacking. In bringing this topic forward, manufacturers can design more appropriate golf grips to reduce the harmful forces and vibrations experienced at the hand/golf grip interface. Providing a more evidence based analysis of the mechanics of arthritis and its relation to sports, the design of more sophisticated sporting equipment and training tools can also be developed. This will help to protect players' joints, and provide customizable equipment for each type of player. This research is also transferable to other racquet, and bat-and-ball sports, whose only contact point, like golf, is the hands. The versatility of this research provides the sports biomechanics field with information that benefits multiple sports, and individuals with and without hand arthritis. In both the sports biomechanics and the clinical field, this research adds to the pool of knowledge surrounding golf biomechanics, and examines the specific interactions at the hand/golf grip interface.

In conclusion, this research used comprehensive evaluations to provide quantitative results that will help reduce the impacts experienced by the hands when performing ADL and when participating in recreational activities such as golf. Having a better understating of this interaction allows for research based golf grip designs, and measurement systems to be developed. These tools would help to maintain healthy golfers' joints, as well as allow golfers with hand arthritis be able to grip their clubs properly and comfortably. Golf is a social and physical activity that can be played at any age. Providing every type of golfer with quality equipment gives the opportunity to bring a new generation of players into the game, and keep those individuals with and without hand arthritis playing.

Bibliography

[1] F. Netter, *Atlas of Human Anatomy*, 7th ed. Elsevier, 2017.

[2] R. J.-M. Tubiana, "In Examination of the hand and wrist." CRC Press, 1998.

[3] "Anatomy," *American Society for Surgery of the Hand*, 2017. [Online]. Available: http://www.assh.org/handcare/hand-arm-anatomy. [Accessed: 17-May-2017].

[4] N. Reese and W. Bandy, *Joint Range of Motion and Muscle Length Testing*, 3rd ed. Elsevier Health Sciences, 2016.

[5] O. J. Lewis, R. J. Hamshere, and T. M. Bucknill, "The anatomy of the wrist joint.," *J Anat*, vol. 106, no. Pt 3, pp. 539–52, 1970.

[6] A. Adams, *The muscular system*. Greenwood Press, 2004.

[7] C. Oatis, *Kinesiology: The Mechanics & Pathomechanics of Human Movement*, 2nd ed. Philadelphia: Lippincott Williams & Wilkins, 2004.

[8] J. Hamill and K. Knutzen, *Biomechanical Basis of Human Motion*, 2nd ed. Lippincott Williams & Wilkins, 2006.

[9] M. Nordin and V. Frankel, *Basic Biomechanics of the Musculoskeletal System*, 3rd ed. Lippincott Williams & Wilkins, Baltimore, 2001.

[10] K. Plewa, J. Potvin, and J. Dickey, "Wrist rotations about one or two axes affect maximum wrist strength," *Appl. Ergonamics*, vol. 53, pp. 152–160, 2016.

[11] A. M. Dollar, "Classifying Human Hand Use and the Activities of Daily Living Activities of daily living," 2014.

[12] M. Cutkosky, "On grasp choice, grasp models, and the design of hands for manufacturing tasks," *IEEE Trans. Robot. Autom.*, vol. 5, no. 3, pp. 269–279, 1987.

[13] H. Clarkson, *Joint Motion and Functional Assessment: A Research-Based Practical Guide*. Lippincott Williams & Wilkins, 2005.

[14] J. Lee and K. Rim, "Measurement of finger joint angles and maximum finger forces during cylinder grip activity," *J. Biomech. Eng.*, vol. 13, no. 2, pp. 152–162, 1991.

[15] I. Carpinella, P. Mazzoleni, M. Rabuffetti, R. Thorsen, and M. Ferrarin, "Experimental protocol for the kinematic analysis of the hand: definition and repeatability," *Gait Posture*, vol. 23, no. 4, pp. 445–454, 2006.

[16] L. Dipietro, A. M. Sabatini, and P. Dario, "Evaluation of an instrumented glove for hand-movement acquisition," no. March, 2003.

[17] M. Vergara, J. Sancho-Bru, and A. Perez-Gonzalez, "Description and Validation of a Non-Invasive Technique to Measure the Posture of All Hand Segments," *J. Biomech. Eng.*, vol. 126, no. 6, pp. 917–922, 2004.

[18] A. Wichelhaus *et al.*, "Parameters influencing hand grip strength measured with

the manugraphy system," *BMC Musculoskelet. Disord.*, vol. 19, no. 1, pp. 1–10, 2018.

[19] V. Mathiowetz, N. Kashman, G. Volland, K. Weber, M. Dowe, and S. Rogers, "Grip and Pinch Strength: Normative Data for Adults," *Occup. Ther. Progr.*, vol. 114, no. 19, pp. 9613–9644, 2014.

[20] T. TAKANO, H. YAMAMOTO, and T. HARA, "Biomechanical Analysis of Grasp Motion Characteristics.," *Trans. Japan Soc. Mech. Eng. Ser. C*, vol. 62, no. 603, pp. 4257–4263, 1996.

[21] Arthritis Society, "The Trust About Arthritis," 2018. [Online]. Available: https://www.arthritis.ca/about-arthritis/what-is-arthritis/the-truth-about-arthritis. [Accessed: 22-Dec-2018].

[22] "Sources of Arthritis Pain," *Arthritis Foundation*, 2019. [Online]. Available: https://www.arthritis.org/living-with-arthritis/pain-management/understanding/types-of-pain.php. [Accessed: 13-Jan-2019].

[23] "Arthritis and Diseases that affect the Hand and Wrist," *Arthritis Foundation*, 2017. [Online]. Available: http://www.arthritis.org/about-arthritis/where-it-hurts/wrist-hand-and-finger-pain/causes/hand-wrist-arthritis.php.

[24] Kleinert Institute, "Joint Protection Program Handbook For People with Arthritis." Kleinert Kutz Hand Care Center, Louisville, Kentucky, pp. 1–22, 1988.

[25] Y. Zhang, J. Niu, M. Kelly-hayes, C. E. Chaisson, P. Aliabadi, and D. T. Felson, "Prevalence of Symptomatic Hand Osteoarthritis and Its Impact on Functional Status," vol. 156, no. 11, pp. 1021–1027, 2002.

[26] "Osteoarthritis," *Mayo Foundation for Medical Education and Research*, 2019. [Online]. Available: https://www.mayoclinic.org/diseases-conditions/osteoarthritis/diagnosis-treatment/drc-20351930. [Accessed: 23-Jan-2019].

[27] J. Tehranzadeh, O. Ashikyan, A. Anavim, and S. Tramma, "Enhanced MR imaging of tenosynovitis of hand and wrist in inflammatory arthritis.," *Skeletal Radiol.*, vol. 35, no. 11, pp. 814–822, 2006.

[28] L. Churchill, "Joint motion: method of measuring and recording." American Academy of Orthopaedic Surgeons, 1965.

[29] R. J. van de Pol, E. van Trijffel, and C. Lucas, "Inter-rater reliability for measurement of passive physiological range of motion of upper extremity joints is better if instruments are used: A systematic review," *J. Physiother.*, vol. 56, no. 1, pp. 7–17, 2010.

[30] L. Pereira, S. Rwakabayiza, E. Lecureux, and B. Jolles, "Reliability of the Knee Smartphone-Application Goniometer in the Acute Orthopedic Setting.," *J. Knee Surg.*, vol. 30, no. 3, pp. 223–230, 2017.

[31] M. Mitsukane, H. Tanabe, K. Sugama, Y. Suzuki, and T. Tsurumi, "Test-retest reliability of goniometric measurements of the range of dart-throwing motion," *J. Phys. Ther. Sci.*, vol. 31, no. 3, pp. 236–241, 2019.

[32] P. M. Quesada, P. A. Brock, and G. S. Rash, “Assessment of Electromagnetic Motion Tracking for Quantitative Measurement of Relative Foot/Shank Motion,” pp. 2–3.

[33] T. M. Bottlang, S. M. Madey, C. M. Steyers, L. Marsh, and T. S. T. D. Brown, “Assessment of Elbow Joint Kinematics in Passive Motion by Electromagnetic Motion Tracking,” no. 9, pp. 1–8, 2000.

[34] L. Cai, Y. Ma, S. Xiong, and Y. Zhang, “Validity and Reliability of Upper Limb Functional Assessment Using the Microsoft Kinect V2 Sensor,” *Appl. Bionics Biomech.*, vol. 2019, pp. 1–14, 2019.

[35] A. M. Valevicius, P. Y. Jun, J. S. Hebert, and A. H. Vette, “Use of optical motion capture for the analysis of normative upper body kinematics during functional upper limb tasks: A systematic review,” *J. Electromyogr. Kinesiol.*, vol. 40, no. February, pp. 1–15, 2018.

[36] A. Brygo, I. Sarakoglou, G. Grioli, and N. Tsagarakis, “Synergy-Based Bilateral Port: A Universal Control Module for Tele-Manipulation Frameworks Using Asymmetric Master–Slave Systems,” *Front. Bioeng. Biotechnol.*, vol. 5, no. April, pp. 1–18, 2017.

[37] C. Prakash, K. Gupta, A. Mittal, R. Kumar, and V. Laxmi, “Passive marker based optical system for gait kinematics for lower extremity,” *Procedia Comput. Sci.*, vol. 45, no. C, pp. 176–185, 2015.

[38] C. R. Mascott, “COMPARISON OF MAGNETIC TRACKING AND OPTICAL TRACKING BY SIMULTANEOUS USE OF TWO INDEPENDENT FRAMELESS STEREOTACTIC SYSTEMS,” vol. 57, no. October, pp. 295–301, 2005.

[39] J. C. Van Den Noort, H. G. Kortier, N. Van Beek, D. H. E. J. Veeger, and P. H. Veltink, “Measuring 3D hand and finger kinematics - A comparison between inertial sensing and an opto-electronic marker system,” *PLoS One*, vol. 11, no. 11, pp. 1–16, 2016.

[40] N. K. Fowler and A. C. Nicol, “A force transducer to measure individual finger loads during activities of daily living,” *J. Biomech.*, vol. 32, no. 7, pp. 721–725, 1999.

[41] N. K. Fowler and A. C. Nicol, “Measurement of external three-dimensional interphalangeal loads applied during activities of daily living,” *Clin. Biomech.*, vol. 14, no. 9, pp. 646–652, 1999.

[42] S. Yao and Y. Zhu, “Wearable multifunctional sensors using printed stretchable conductors made of silver nanowires,” *Nanoscale*, vol. 6, no. 4, pp. 2345–2352, 2014.

[43] “Wearable Contact Force Sensor,” *HapLog Haptic Skill Logger*, 2011. [Online]. Available: http://english.keskato.co.jp/products/haplog.html. [Accessed: 02-Feb-2019].

[44] A. Palmer, *Arnold Palmer’s Golf Book; “Hit It Hard!”* New York: The Ronald

Press Company, 1961.

[45] A. Agent and F. D.- Gil, “United States Patent [19],” 1996.

[46] A. Hay, “The Mechanics of Golf.” St. Martin’s Press; Robert Hale, New York, London, 1979.

[47] O. Publications, “United States Patent [191 I [11] Patent Number : [45] Date of Patent :,” no. 19, 1991.

[48] M. Stachura, “Number of golfers steady, more beginners coming from millennials,” *Golf Digest*. [Online]. Available: http://www.golfdigest.com/story/number-of-golfers-steady-more. [Accessed: 19-Jun-2017].

[49] “What’s your handicap?,” *Golf Canada*. [Online]. Available: http://golfcanada.ca/article/whats-your-handicap. [Accessed: 10-Jan-2019].

[50] R. Preston, “What Is the Average Golf Handicap in America?,” *Golfweek*. [Online]. Available: https://golftips.golfweek.com/average-golf-handicap-america-2455.html. [Accessed: 15-May-2019].

[51] C. A.P., V. A.A., and L. D.M., “Optimizing the benefits versus risks of golf participation by older people,” *J. Geriatr. Phys. Ther.*, vol. 28, no. 3, pp. 85–92, 2005.

[52] Y. Chu, T. C. Sell, and S. M. Lephart, “The relationship between biomechanical variables and driving performance during the golf swing,” *J. Sports Sci.*, vol. 28, no. 11, pp. 1251–1259, 2010.

[53] “A History of the Golf Club,” *Golf Europe*, 2017. [Online]. Available: http://www.golfeurope.com/almanac/history/golf_club1.htm. [Accessed: 09-Jun-2017].

[54] “Golf Pride Grips,” 2019. [Online]. Available: https://www.golfpride.com/grips/. [Accessed: 16-Jan-2019].

[55] “Golf Glove Buying Guide,” *Golf A Lot*, 2019. [Online]. Available: http://www.golfalot.com/buyingguides/gloves.aspx. [Accessed: 24-Jan-2019].

[56] B. Hill, “History of the Golfing Glove,” *Golfweek*, 2019. [Online]. Available: https://golftips.golfweek.com/history-golfing-glove-1540.html. [Accessed: 24-Jan-2019].

[57] E. Komi, “High Speed Video Footage for Enhanced Evaluation of Grip Force Signatures in Golf,” in *Science and Golf V: Proceedings of the World Scientific Congress of Golf*, 2008, pp. 60–66.

[58] “Arthritis Facts,” *Arthritis Foundation*, 2017. [Online]. Available: http://www.arthritis.org/about-arthritis/understanding-arthritis/arthritis-statistics-facts.php. [Accessed: 20-Feb-2017].

[59] G. Elkoura and K. Singh, “Handrix : Animating the Human Hand,” 2003.

[60] R. Khadem *et al.*, “Comparative tracking error analysis of five different optical tracking systems,” *Comput. aided Surg. Off. J. Int. Soc. Comput. Aided Surg.*, vol.

5, no. 2, pp. 98–107, 2000.

[61] L. Pereira, S. Rwakabayiza, E. Lecureux, and B. Jolles, “Reliability of the Knee Smartphone-Application Goniometer in the Acute Orthopedic Setting.,” *J. Knee Surg.*, vol. 30, no. 3, pp. 223–230, 2017.

[62] L. Caruso, R. Russo, and S. Savino, “Microsoft Kinect V2 vision system in a manufacturing application,” *Robot. Comput. Integr. Manuf.*, vol. 48, pp. 174–181, 2017.

[63] S. Borel, P. Schneider, and C. J. Newman, “Gait & Posture Video analysis software increases the interrater reliability of video gait assessments in children with cerebral palsy,” *Gait Posture*, vol. 33, no. 4, pp. 727–729, 2011.

[64] L. Khadilkar, J. MacDermid, K. Sinden, T. Jenkyn, T. Birmingham, and G. Athwal, “An analysis of functional shoulder movements during task performance using Dartfish movement analysis software,” *Int. J. Shoulder Surg.*, vol. 8, no. 1, pp. 1–9, 2014.

[65] J. C. MacDermid, T. Turgeon, R. S. Richards, M. Beadle, and J. H. Roth, “Patient Rating of Wrist Pain and Disability: A Reliable and Valid Measurement Tool,” *J. Orthop. Trauma*, vol. 12, no. 8, pp. 577–586, 1998.

[66] “The Patient-Rated Wrist Evaluation (PRWE) User Manual June 2011 1,” no. June, 2011.

[67] A. Training, B. Palpation, and S. Sheet, “AH 321 Assessment of Athletic Injuries / Illnesses Laboratory,” pp. 3–5, 2018.

[68] S. Mayr, E. Erdfelder, A. Buchner, and F. Faul, “A short tutorial of GPower,” *Tutorials in Quantitative Methods for Psychology*, vol. 3, no. 2. pp. 51–59, 2007.

[69] S. Skrivanek and M. Com Llc, “Power of a Statistical Test What is the power of a test?,” 2009.

[70] M. Eltoukhy, S. S. Asfour, C. Thompson, and L. Latta, “Evaluation of the Performance of Digital Video Analysis of Human Motion : Dartfish Tracking System,” no. June 2014, 2012.

[71] Statista Survey, “Share of Americans who played golf in the last 12 months in 2018 , by age.” 2018.

[72] “Arthritis, by age group,” *Statistics Canada*, 2017. [Online]. Available: https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=1310009606. [Accessed: 04-Feb-2019].

[73] “TrackMan Golf,” 2019. [Online]. Available: https://trackmangolf.com/.

[74] D. R. Budney and D. G. Bellow, “Evaluation of golf club control by grip pressure measurement,” in *Proceedings of the World Scientific Congress of Golf Science and Golf I*, 1990.

[75] J. Broker and M. Ramey, “Understanding Golf Club Control Through Grip Pressure Measurement,” in *Science and Golf V: Proceedings of the World Scientific Congress of Golf*, 2008, pp. 52–59.

[76] T. D. Cahalan, W. P. Cooney, K. Tamai, and E. Y. s. Chao, “Biomechanics of the golf swing in players with pathologic conditions of the forearm, wrist, and hand,” *Am. J. Sports Med.*, vol. 19, no. 3, pp. 288–293, 1991.

[77] “Arthritis Golf Grips,” *Lamkin*, 2017. [Online]. Available: https://www.lamkingrips.com/shop/arthritic-golf-grips.html/. [Accessed: 22-Feb-2017].

[78] “Golf Grips Buying Guide,” *Golf A Lot*. [Online]. Available: http://www.golfalot.com/buyingguides/grips.aspx. [Accessed: 19-Jun-2017].

[79] “Grips and Gloves for All Golfers, Especially those with Hand-Strength Challenges,” *Quantum Grip*, 2017. [Online]. Available: http://www.quantumgrip.com/. [Accessed: 22-Feb-2017].

[80] “Tacki-Mac Golf Oversized Arthritic Grip Black,” *Rock Bottom Golf*. [Online]. Available: https://www.rockbottomgolf.com/golf-clubs/club-making-gear/grips/tacki-mac-oversized-arthritic-golf-grip-men-black/. [Accessed: 04-Mar-2019].

[81] “Excel Wrap Oversize,” *winn*, 2019. [Online]. Available: http://www.winngrips.com/products/excel-wrap/excel-wrap-oversize/. [Accessed: 04-Mar-2019].

[82] “Frequently Asked Questions,” *Golf Pride Grips*, 2017. [Online]. Available: http://www.golfpride.com/faqs/technology/. [Accessed: 11-May-2017].

[83] “Capacitive Tactile Pressure Sensors,” *Pressure Profile Systems*, 2018. [Online]. Available: https://pressureprofile.com/capacitive-sensors. [Accessed: 01-Jan-2018].

[84] R. Sasikumar and K. Lenin, “Assessing the influence of hand-arm posture on mechanical responses of the human hand during drilling operation,” *Int. J. Adv. Manuf. Technol.*, vol. 93, no. 1–4, pp. 375–384, 2017.

[85] G. Kulothungan, M. Nachiappan, M. S. Kumar, and S. Rajasekaran, “Comparative Study of Forces Involved in Different Styles of Handwriting,” *J. Autom. Control Eng.*, vol. 1, no. 3, pp. 260–264, 2013.

[86] “After analyzing 1,440 swings, we discovered that 9 out of 10 golfers play the wrong-sized grips,” *Golf.com*. 2013.

[87] H. Carson, D. Collins, and J. Richards, “‘To Hit, of Not to Hit?’ Examining the Similarity Between Practice and Real Swings in Golf,” *Int. J. Golf Sci.*, vol. 2, pp. 103–118, 2014.

[88] D. . Noble, “An analysis of hand grip as a factor influencing the power of the golf swing.” Golf Society of Great Britain; Scientific Working Party, 1963.

[89] S. H. Katsuyuki Sakuma, Avner Abrami, Gaddi Blumrosen, Stanislav Lukashov, Rao Narayana, Joseph Ligman, Vittorio Caggiano, “Wearable Nail Deformation Sensing for Behavioral and Biomechanical Monitoring and Human-Computer Interaction,” *Submitted*, no. August, pp. 1–11, 2018.

[90] S. Holland and M. Elliott, “Interview.” 2017.

[91] E. Demircan, T. F. Besier, and O. Khatib, “Muscle force transmission to operational space accelerations during elite golf swings,” *Proc. - IEEE Int. Conf. Robot. Autom.*, pp. 1464–1469, 2012.

[92] S. Mahadas, K. Mahadas, and G. K. Hung, “Biomechanics of the golf swing using OpenSim,” *Comput. Biol. Med.*, vol. 105, no. August 2018, pp. 39–45, 2019.

[93] “Arthritis, by age group,” *Statistics Canada*, 2017. .

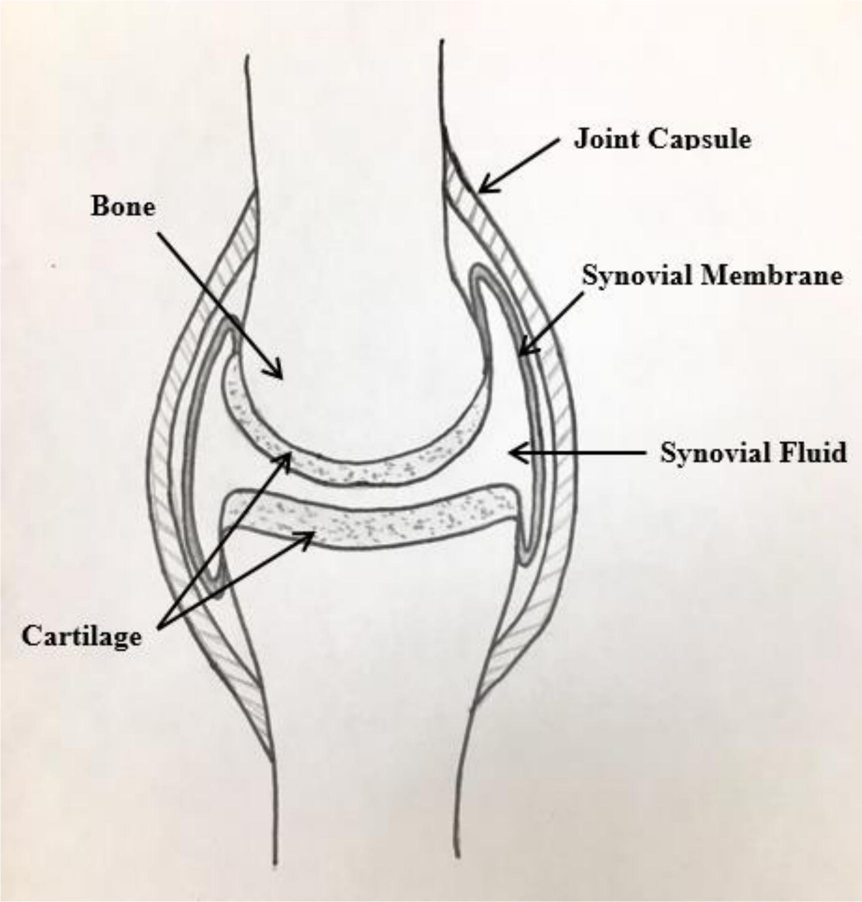
[94] “Durometer Shore Hardness Scale,” *Smooth-On*, 2019. [Online]. Available: https://www.smooth-on.com/page/durometer-shore-hardness-scale/. [Accessed: 04-Mar-2019].

[95] B. Reuss, “Convery Durometer to Young’s Modulus,” *Computer Aided Technology*, 2011. [Online]. Available: https://www.cati.com/blog/2011/07/convert-durometer-to-youngs-modulus/. [Accessed: 30-Mar-2019].

[96] “REDCap,” *Lawson Health Research Institute*, 2019. [Online]. Available: https://redcap.lawsonresearch.ca/. [Accessed: 08-Apr-2018].

Appendices

Appendix A – Synovial Joint Structure (Chapter 1)

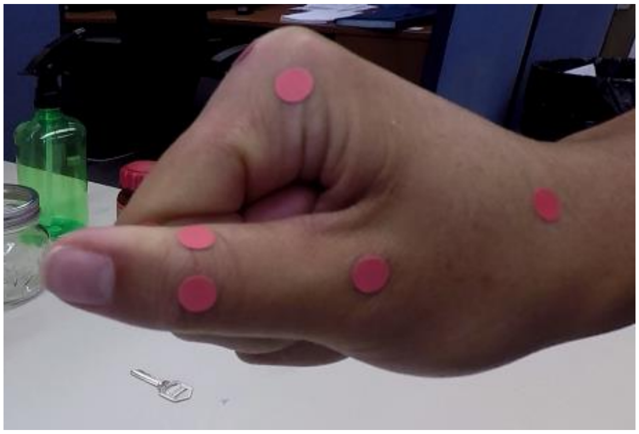


Appendix B – Gripping Style Variations (Chapter 2)

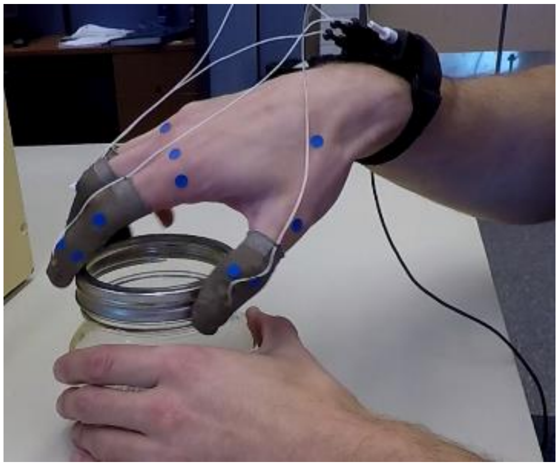
Two variations of gripping styles were seen during the maximum flexion and large jar task performed during the study conducted in Chapter 2. The pair of gripping styles are shown below and were found to have no significant effect on the grip configuration measures obtained.

B1. Normal Fist Position

B2. Overlapping Fist Position



B3. Fingertip Gripping Style for the Large Jar Task



B4. Palm Gripping Style for the Large Jar Task

Appendix C – Specifications of the Golf Grips (Chapter 3)

This section presents detailed specifications on each of the golf grips used in Chapter 3. The material compliance of each of the 12 golf grips was measured using a type A durometer (ASTM 2240). The shore A hardness scale was used to categorize the firmness of the materials, as this scale is used for flexible mold rubbers [94]. The values obtained from the durometer measurements were converted to a Young's Modulus value. The empirically derived mathematical formula for the conversion is shown below in Equation 3 [95]:

$$E = e^{(Shore\ A)(0.0235)-0.6403}\ \text{[MPa]} \qquad \textbf{(Equation 3)}$$

The charts below show the material compliance values from the durometer measures, with the conversions to Young's Modulus for each golf grip. These values assisted in categorizing the material composition of the 'arthritic' designed golf grips into soft, medium, and hard firmness. Each grips top and bottom circumference (CIRC) are also presented.

C1. Golf Pride CP2 Pro Grip Properties

Grip Name	Material Class	Material Compliance [Shore A]	Young's Modulus [MPa]	Geometry Size	Top CIRC [mm]	Bottom CIRC [mm]
CP2 Pro	Soft Firmness	43	1.52	(1) Jumbo	9.4	6.8
		46	1.55	(2) Mid-Sized	9	6.2
		42	1.41	(3) Standard	8.5	6
		46	1.55	(4) Undersized	8.3	5.9

(1)

(2)

(3)

(4)

C2. Golf Pride MCC PLUS4 Grip Properties

Note: The MCC PLUS4 Grip designs are made of two different material classifications being a hard firmness material on the top of the grip (on the left side of the images below), and softer firmness on the bottom of the grip (on the right side of the images below) [54].

Grip Name	**Material Class**	**Material Compliance (Top/Bottom) [MPa]**	**Young's Modulus (Top/Bottom) [MPa]**	**Geometry Size**	**Top CIRC [mm]**	**Bottom CIRC [mm]**
MCC PLUS4	Medium Firmness	45/72	1.52/2.86	(1) Mid-Sized	9.2	6.5
		46/71	1.55/2.80	(2) Standard	8.6	6
		46/72	1.55/2.86	(3) Undersized	8.6	5.9

(1)

(2)

(3)

C3. Golf Pride Z-Grip Grip Properties

Grip Name	Material Class	Material Compliance [MPa]	Young's Modulus [MPa]	Geometry Size	Top CIRC [mm]	Bottom CIRC [mm]
Z-Grip	Hard Firmness	73	2.93	(1) Mid-Sized	9.1	5.8
		82	3.62	(2) Standard	8.4	5.8

(1)

(2)

C4. Lamkin Arthritis Grip Properties

Grip Name	Material Class	Material Compliance [MPa]	Young's Modulus [MPa]	Geometry Size	Top CIRC [mm]	Bottom CIRC [mm]
Lamkin Arthritis Grip	Medium Firmness	50	1.71	Standard	8.5	6.1

C5. Tacki-Mac Arthritis Serrated Standard Grip Properties

Grip Name	Material Class	Material Compliance [MPa]	Young's Modulus [MPa]	Geometry Size	Top CIRC [mm]	Bottom CIRC [mm]
Tacki-Mac Arthritis Grip	Medium Firmness	55	1.92	Standard	8.5	6

C6. Winn Excel Soft Oversized Grip Properties

Grip Name	Material Class	Material Compliance [MPa]	Young's Modulus [MPa]	Geometry Size	Top CIRC [mm]	Bottom CIRC [mm]
Winn Excel Soft Oversized Grip	Medium Firmness	65	2.43	Mid-Sized	8.8	7.7

Appendix D – Study Letter of Information and Consent Form (Chapter 3)

Protect Title: The Comparison of Golf Grips to Hand Forces in Individuals with and without Hand Arthritis

Investigators: **Dr. Emily Lalone, PhD (Principal Investigator)**
Dr. Louis Ferreira, PhD
Dr. James Dickey, PhD
Sara Holland, M.E.Sc Candidate 2019

What is the purpose?

You are being invited to voluntarily participate in a research study that examines the effects of different golf grips on hand forces. With diagnosed arthritis affecting 1 in 5 adults in Canada and with an increasingly aging population, playing sports such as golf becomes difficult. The grip of a golf club is the only contact point between the player and the club, making the player's gripping force and the golf grip itself important elements of the game. However, the golf grip is the most overlooked piece of equipment in a player's bag. Comprehensive examinations have not been done on current golf grips and a small amount of arthritis golf grips have recently been marketed but are not based on empirical measurements nor have they been properly tested to determine their effectiveness at reducing joint pain in a players hands. In order to study these acute forces, a commercially available capacitive finger sensor system designed by Pressure Profile System (FingerTPS sensors) will be used to measure the forces in the fingers. There are two patient groups in this full study; participants with hand arthritis and participants who do not have hand arthritis.

Study Procedures:

We will ask you to come to our Thames Hall Biomechanics Laboratory at Western University where first you will then be given a survey to fill out which asks you about your current pain in your hands and some background about your golf game and the equipment you use. We will then sit down with you and secure the FingerTPS finger cot sensors, consisting of micro spandex material, to your fingers. There will be wires that run along the back of your arm that are attached to a receiver that will be attached to a belt worn around your waist. We will then measure your grip strength and if you feel comfortable, we will ask you to perform full swings with each of the 12 different grips. We hope to record and take photos of the activities performed using video recording and photography. This is optional where you can choose to consent to this by checking the boxes on the attached consent form. The entire protocol will take approximately 1 hour. The finger sensors then easily slide off your fingers and finally we will ask that you fill out a questionnaire about your experience with the finger sensors.

Potential benefits of participating in this study:

You may not personally benefit from participation in this study. However, the results might improve outcomes for patients with hand arthritis that wish to continue to play golf.

Is there any compensation?

There is no payment for participating in this study. We will provide parking passes on the days that you visit our research laboratory at Western University.

Potential risk or discomforts associated with this study:

There are no potential risks associated with this study. If any of the functional tasks cause any amount of pain we will stop the assessment.

How many people will be in this study?

There will be approximately 200 people participating in this study.

Will my results be kept confidential?

The overall results of the study will be available to you upon request. Your individual results will be held in strict confidence. No person, other than the study team, will have access to your study related records without your permission. Your data that is stored in the database will have your personal identifying information removed or coded so that the study database will be de-identified. This database is located on a secure Hospital and University network and will be stored indefinitely. A master list is located in a locked cabinet within the lab which is also locked daily. Western's Health Sciences Research Ethics Board (HSREB) and Lawson's Quality Assurance Education Program (QAEP) may access the data for quality assurance purposes. Photos and videos taken during the study will be used for publication purposes if you agree.

Alternatives to Study Participants:

Participation in this study is voluntary. You may refuse to participate, refuse to answer any questions or withdraw from the study at any time. You will receive a copy of this letter of information and consent form for your records. You do not have to waive any of your legal rights by signing this consent form.

Whom may you contact to find out more about this study?

You will be given a copy of this letter and the signed consent form. If you have questions about taking part in this study, you can directly contact the Principal Investigator Dr. Lalone.

If you have any questions about your rights as a research participant or the conduct of this study, you may contact The Office of Human Research Ethics. The REB is a group of people who oversee the ethical conduct of research studies. The HSREB is not part of the study team. Everything that you discuss will be kept confidential.

Consent From

<u>Consent to Participate in: The Comparison of Golf Grips to Hand Forces in Individuals with and without Hand Arthritis</u>

I have read the Letter of Information, have had the nature of the study explained to me and I agree to participate. All questions have been answered to my satisfaction.

I am willing to have this session video recorded: ○ yes ○no

I am willing to have photos taken during this session: ○ yes ○no

I agree to have my photos/videos taken during this session used for publication purposes: ○ yes ○no

______________________	______________________	______________________
Signature of Participant	Print Name	Date
______________________	______________________	______________________
Signature of person obtaining consent	Print Name of person obtaining consent	Date

Appendix E – Participant Survey and Data Results (Chapter 3)

E1. Survey Questions

Golf Participant Survey

Study ID:	
Date:	

Thank you for participating in this study. These questions will provide us with some background information that will be used to help monitor and analyse how golf grips relates to hand forces and arthritis (if applicable). If you are unsure about how to answer a question, please ask for help.

1. Sex
☐ Male
☐ Female

2. What is your age range?
☐ 18-35
☐ 36-50
☐ 51-65
☐ 65+

3. What is your dominant hand?
☐ Right
☐ Left

4. What hand golfer are you?
☐ Right
☐ Left

Survey V1, January 13, 2018

5. What is your **handicap** or **average scoring range** (ex. 75 to 85)? If you do not know, check the unsure box.

Handicap: ______________________________

Average Scoring Range: ______________________________
☐ Unsure

6. Do you wear a golf glove and if so, on which hand(s)?
☐ Right Hand
☐ Left Hand
☐ Both Hands
☐ Do not wear a glove

7. What type of golf **gripping style** do you use?
☐ Overlapping (fingers overlay)
☐ Interlocking (fingers interlace)
☐ Baseball grip (ten fingers)
☐ Unsure

8. Are you able to touch your finger tips to the palm of your hand(s) (make a fist)?

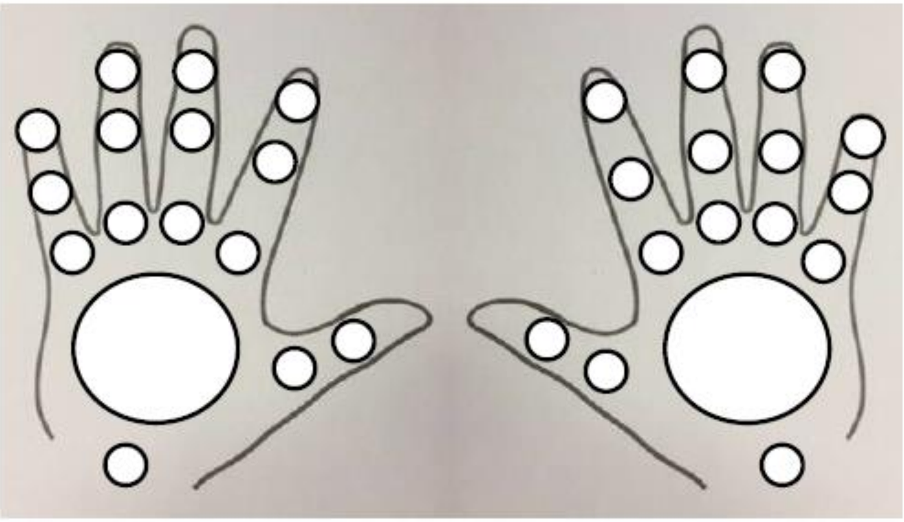
Left:	Right:
☐ Yes	☐ Yes
☐ No	☐ No

9. Have you had any hand/wrist injuries in the last year (ex. broken bones, sprains, ligament tears, carpal tunnel etc.)?

☐ Yes

☐ No

If yes, please indicate where in your hand(s)/wrist(s) by placing an **X** in the circles below.

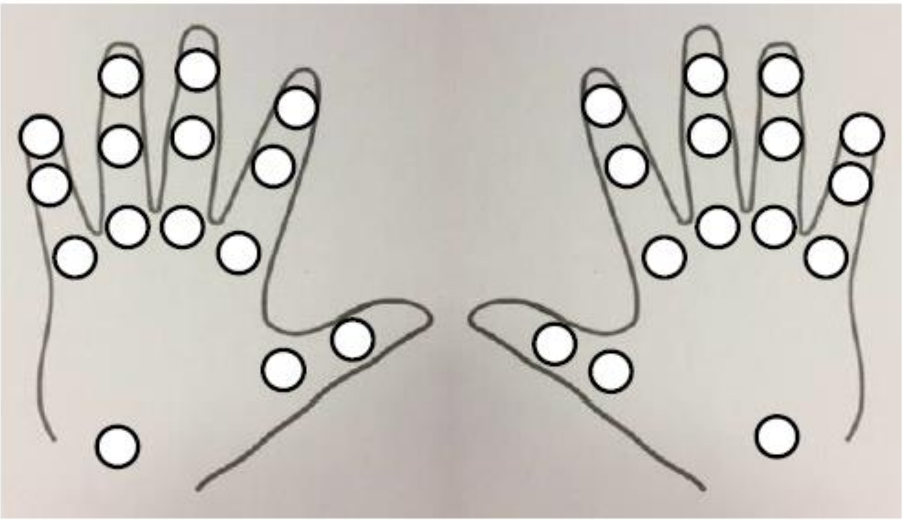


10. Do you have arthritis in your hand(s)/wrist(s)?

☐ Yes

☐ No

If yes, please indicate where in your hand(s)/wrist(s) by placing an **X** in the circles below.



11. If you have arthritis in your hand(s), what type of arthritis is it?
☐ Osteoarthritis
☐ Rheumatoid Arthritis
☐ Psoriatic Arthritis
☐ Not Applicable
☐ Other: ____________________

12. How long have you had arthritis in your hand(s)?
☐ Less than 1 year
☐ Between 1 and 10 years
☐ More than 10 years
☐ Not Applicable

13. Has the arthritis in your hand(s) affected your gripping style and performance?
☐ Yes
☐ No
☐ Not Applicable
If yes, please explain: ____________________

14. Did you have to change your gripping style or golf grips, to accommodate for your arthritis?
☐ Grips
☐ Gripping Style (overlapped, interlocking, baseball grip)
☐ Both
☐ Neither
☐ Not Applicable

15. Would you buy new golf grips if they could have a positive influence on your game?
☐ Yes
☐ No

16. Do you feel that the manufacture and development of golf grips can reduce unnecessary or potentially physically damaging "vibration" on miss-hit shots?
☐ Yes
☐ No

17. Do you feel that improved golf grips could help individuals with hand arthritis?
☐ Yes
☐ No

E2. Survey Results

Participant	Sex	Age	Dominant Hand	Hand Golfer	Scoring Range	Handicap
109390_03	Female	18-35	Right	Right		3.4
109390_04	Female	18-35	Right	Right	Unsure	Unsure
109390_05	Male	36-50	Right	Left		0
109390_06	Male	18-35	Right	Right		1.1
109390_07	Female	18-35	Right	Right	88-95	17
109390_08	Male	36-50	Right	Left		1
109390_09	Male	18-35	Right	Right		3
109390_10	Male	36-50	Right	Right		15
109390_11	Male	50-65	Right	Left	80-90	
109390_12	Male	50-65	Right	Right		5
109390_13	Female	65+	Right	Right	Unsure	Unsure
109390_14	Male	50-65	Right	Right	100	
109390_15	Female	65+	Right	Right	120	40
109390_16	Male	50-65	Right	Right	80-85	12
109390_17	Male	18-35	Right	Left	78-84	10
109390_18	Male	50-65	Left	Right		10
109390_19	Female	18-35	Right	Right	80-89	13
109390_20	Male	18-35	Right	Right	Unsure	Unsure
109390_22	Female	65+	Right	Right	90-95	
109390_24	Female	65+	Right	Right	84	18
109390_25	Male	65+	Left	Right	72-82	4
109390_26	Male	50-65	Right	Right	75-78	6
109390_28	Female	50-65	Right	Right	80-85	10
109390_29	Female	65+	Left	Right		12.9
109390_31	Female	18-35	Right	Right	Unsure	Unsure
109390_32	Male	36-50	Right	Right	75-80	5
109390_33	Female	50-65	Right	Right	95	

Continued

Glove	Gripping Style	Left Fist	Right Fist	Hand/Wrist Injuries
Left	Interlocking	Yes	Yes	No
Do not wear a glove	Overlapping	Yes	Yes	No
Right	Overlapping	Yes	Yes	No
Right	Interlocking	Yes	Yes	No
Left	Overlapping	Yes	Yes	No
Do not wear a glove	Overlapping	Yes	Yes	Yes

Left	Overlapping	Yes	Yes	No
Left	Interlocking	Yes	Yes	No
Right	Overlapping	Yes	Yes	No
Both Hands	Interlocking	Yes	Yes	No
Left	Interlocking	No	No	No
Both Hands	Baseball	Yes	Yes	No
Left	Interlocking	Yes	Yes	No
Both Hands	Overlapping	No	No	No
Right	Interlocking	Yes	Yes	No
Left	Interlocking	Yes	Yes	No
Right	Interlocking	Yes	Yes	No
Do not wear a glove	Baseball	Yes	Yes	No
Both Hands	Interlocking	Yes	Yes	No
Both Hands	Baseball	No	No	No
Do not wear a glove	Interlocking	yes	Yes	Yes
Left	Overlapping	Yes	Yes	No
Do not wear a glove	Overlapping	Yes	Yes	No
Left	Baseball	Yes	Yes	No
Do not wear a glove	Interlocking	Yes	Yes	No
Left	Baseball	Yes	Yes	No
Left	Overlapping	Yes	Yes: more difficult	Yes

Continued

Hand/Wrist Arthritis	Type of Arthritis	Time Since Diagnosis
No	Not Applicable	Not Applicable
No	Not Applicable	Not Applicable
No	Not Applicable	Not Applicable
No	Not Applicable	Not Applicable
No	Not Applicable	Not Applicable
No	Not Applicable	Not Applicable
No	Not Applicable	Not Applicable
No	Not Applicable	Not Applicable
No	Not Applicable	Not Applicable
No	Not Applicable	Not Applicable
Yes	Osteoarthritis	Between 1 and 10 years
Yes	Osteoarthritis	More than 10 years
Yes	Osteoarthritis	More than 10 years
Yes	Osteoarthritis	Between 1 and 10 years
No	Not Applicable	Not Applicable
No	Not Applicable	Not Applicable

No	Not Applicable	Not Applicable
No	Not Applicable	Not Applicable
Yes	Osteoarthritis	More than 10 years
Yes	Osteoarthritis	Between 1 and 10 years
Yes	Osteoarthritis	Between 1 and 10 years
Yes	Osteoarthritis	More than 10 years
No	Not Applicable	Not Applicable
Yes	Osteoarthritis	More than 10 years
No	Not Applicable	Not Applicable
No	Not Applicable	Not Applicable
Yes	Osteoarthritis	Between 1 and 10 years

Continued

Arthritis/Grip Affect	**Arthritis/Grip Change**	**Golf Grip Purchase Influence**	**Grip Manufacturing**	**Improved Grip Design Help Arthritis**
Not Applicable	Not Applicable	Yes	Yes	Yes
Not Applicable	Not Applicable	No	Yes	Yes
Not Applicable	Not Applicable	Yes	Yes	Yes
Not Applicable	Not Applicable	Yes	Yes	Yes
Not Applicable	Not Applicable	Yes	Yes	Yes
Not Applicable	Not Applicable	Yes	Yes	Yes
Not Applicable	Not Applicable	Yes	Yes	Yes
Not Applicable	Not Applicable	Yes	Yes	Yes
Not Applicable	Not Applicable	Yes	Yes	Yes
Not Applicable	Not Applicable	Yes	Yes	Yes
Yes: pain while gripping	Gripping Style	No	Yes	Yes
Yes	Grips, Gripping Style	Yes	Yes	Yes
Yes: adjust grip to get more comfortable	Neither	Yes	Yes	Yes
Yes	Grips	Yes	Yes	Yes
Not Applicable	Not Applicable	Yes	Yes	Yes
Not Applicable	Not Applicable	Yes	Yes	Yes
Not Applicable	Not Applicable	Yes	Yes	Yes
Not Applicable	Not Applicable	No	Yes	Yes
Yes: Grip is weakened	Grips	Yes	Yes	Yes
Yes	Both	Yes	Yes	Yes

Yes: Affects interlocking grip	Grips, Gripping style	Yes	Yes	Yes
Yes	Grips	Yes	Yes	Yes
Not Applicable	Not Applicable	Yes	Yes	Yes
Yes: not able to do overlay	Gripping Style	Yes	Yes	Yes
Not Applicable	Not Applicable	Yes	Yes	Yes
No	Not Applicable	Yes	Yes	Yes
Yes: weaker grip	Grips	Yes	Yes	Yes

Appendix F – Online Survey and Data Results (Chapter 3)

A survey consisting of 26 questions (overall n=54) was distributed through an online platform known as RedCap (Research Electronic Dara Capture) version 6.11.3 hosted by Lawson Health Research Institute [96]. The survey questions consisted of general background questions about people's golf games, if they have hand arthritis and their opinions on the importance of golf grips. The survey and results of this survey are presented below.

F1. Online Survey Questions

Golf Participant Survey

Study ID:	
Date:	

Thank you for participating in this study. These questions will provide us with some background information that will be used to help monitor and analyse how golf grips relates to hand forces and arthritis (if applicable). If you are unsure about how to answer a question, please ask for help.

1. Sex
   - ☐ Male
   - ☐ Female

2. What is your age range?
   - ☐ 18-35
   - ☐ 36-50
   - ☐ 50-65
   - ☐ 65+

3. What is your dominant hand?
   - ☐ Right
   - ☐ Left

4. What hand golfer are you?
   - ☐ Right
   - ☐ Left

Survey V4, January 28, 2018

5. What is your **handicap** or **average scoring range** (ex. 75 to 85)? If you do not know, check the unsure box.

Handicap: ______________________________

Average Scoring Range: ______________________________

☐ Unsure

6. Do you wear a golf glove and if so, on which hand(s)?

☐ Right Hand
☐ Left Hand
☐ Both Hands
☐ Do not wear a glove

7. If you wear a golf glove, is it for/because?

☐ Feels comfortable (part of your routine)
☐ To prevent blisters or calluses on your hand(s)
☐ To create more traction/grip/friction between your hand(s) and the grip
☐ Other

8. What type of golf **gripping style** do you use?

☐ Overlapping (fingers overlay)
☐ Interlocking (fingers interlace)
☐ Baseball grip (ten fingers)
☐ Unsure

9. What **brand** of golf grips do you use on your irons? Please select all that apply.

☐ Golf Pride
☐ Winn
☐ Lamkin
☐ Unsure
☐ Other

10. What **type** of golf grips do you use on your irons? Please select all that apply.

☐ Rubber
☐ Corded
☐ Wrap
☐ Unsure

11. Do you use the same type of golf grips for all of your clubs (except putter)?
☐ Yes
☐ No
If no, why? ____

12. What is the firmness of your golf grips on your irons? Please select all that apply.
☐ Hard
☐ Medium
☐ Soft
☐ Unsure

13. What is the size of your golf grips on your irons? Please select all that apply.
☐ Standard
☐ Undersized
☐ Mid-sized
☐ Jumbo
☐ Unsure

14. How often do you re-grip your golf clubs?
☐ Every season (once a year)
☐ Every other season (once every two years)
☐ Have not re-gripped my clubs
☐ Other

15. Do you find anything wrong or uncomfortable with your current golf grips on your irons?
☐ Yes
☐ No
If yes, why? ____

16. On miss-hit shots, would you characterise the "vibration" you receive in your hands as?
☐ Minimal (feels like a normal shot)
☐ Slight sensation (tingle, doesn't last long)
☐ Significant (numbness, lasts for about a minute)

17. Are you able to touch your finger tips to the palm of your hand(s) (make a fist)?

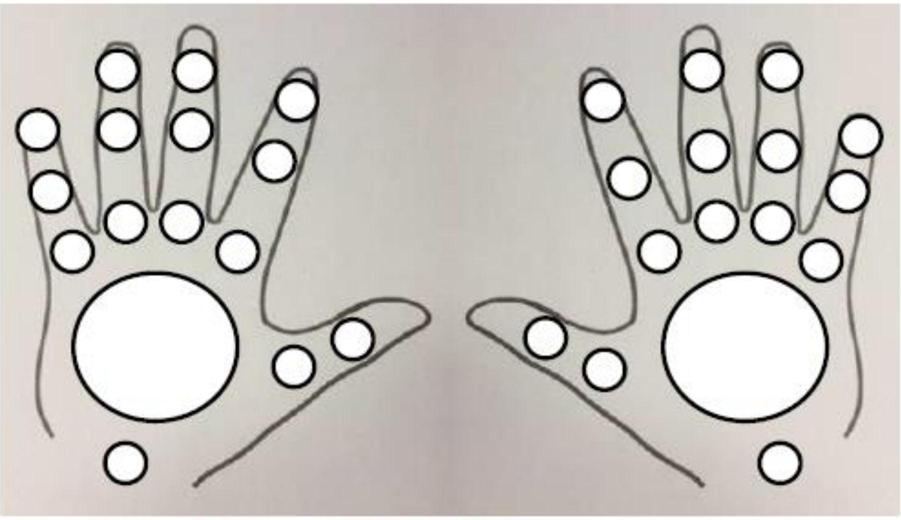
Left:	Right:
☐ Yes	☐ Yes
☐ No	☐ No

18. Have you had any hand/wrist injuries in the last year (ex. broken bones, sprains, ligament tears, carpal tunnel etc.)?

☐ Yes

☐ No

If yes, please indicate where in your hand(s)/wrist(s) by placing an **X** in the circles below.

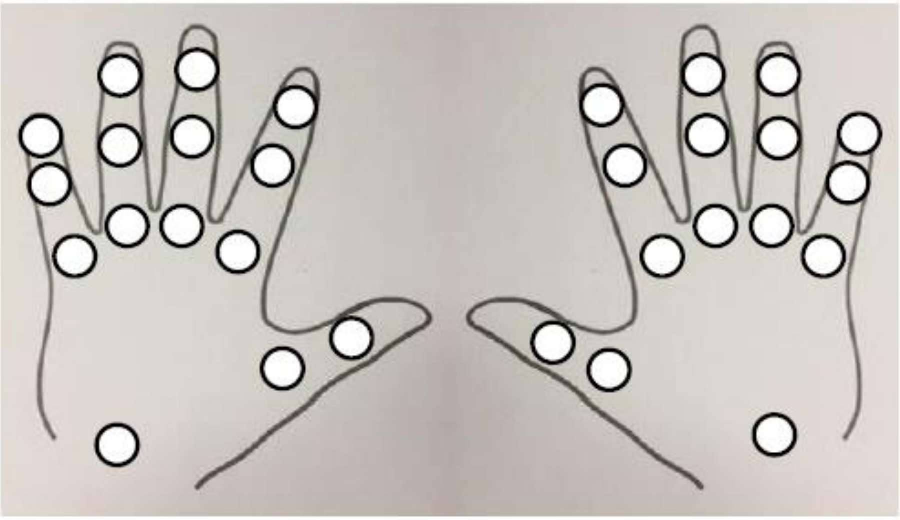


19. Do you have arthritis in your hand(s)/wrist(s)?

☐ Yes

☐ No

If yes, please indicate where in your hand(s)/wrist(s) by placing an **X** in the circles below.



20. If you have arthritis in your hand(s), what type of arthritis is it?

☐ Osteoarthritis
☐ Rheumatoid Arthritis
☐ Psoriatic Arthritis
☐ Not Applicable
☐ Other: ____

21. How long have you had arthritis in your hand(s)?

☐ Less than 1 year
☐ Between 1 and 10 years
☐ More than 10 years
☐ Not Applicable

22. Has the arthritis in your hand(s) affected your gripping style and performance?

☐ Yes
☐ No
If yes, please explain: ____________________________________

23. Did you have to change your gripping style or golf grips, to accommodate for your arthritis?

☐ Grips
☐ Gripping Style (overlapped, interlocking, baseball grip)
☐ Both
☐ Neither
☐ Not Applicable

24. Would you buy new golf grips if they could have a positive influence on your game?

☐ Yes
☐ No

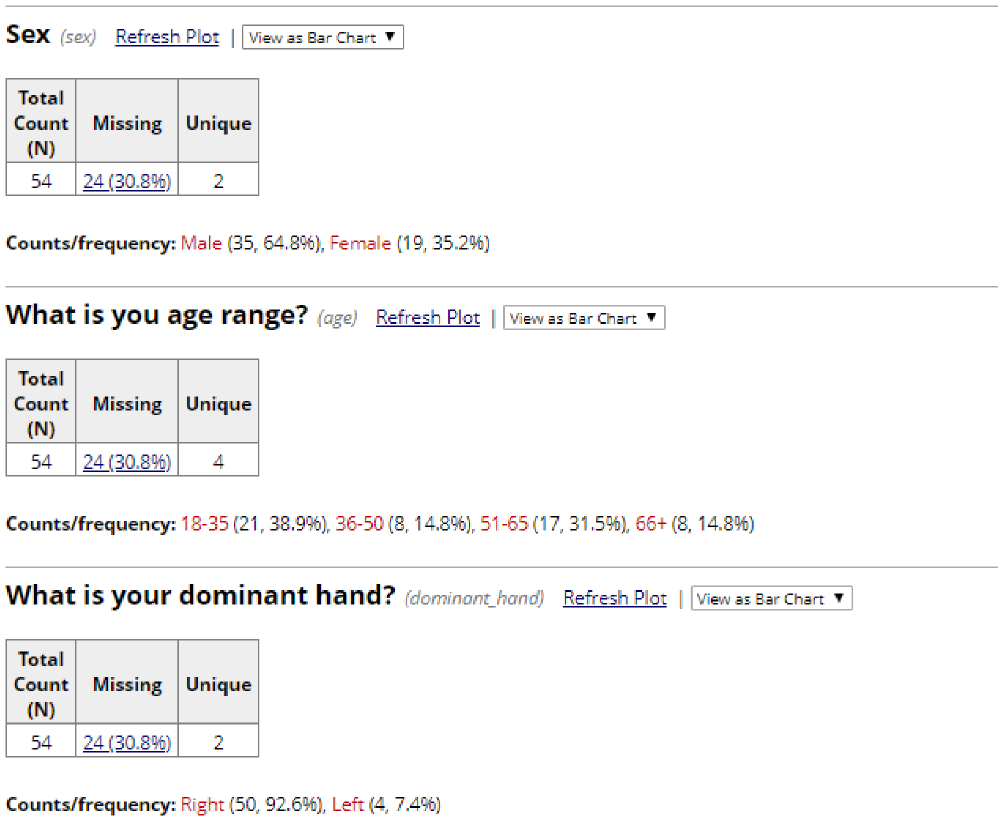
25. Do you feel that the manufacture and development of golf grips can reduce unnecessary or potentially physically damaging "vibration" on miss-hit shots?

☐ Yes
☐ No

26. Do you feel that improved golf grips could help individuals with hand arthritis?

☐ Yes
☐ No

F2. Online Survey Results



Sex *(sex)*

Total Count (N)	Missing	Unique
54	24 (30.8%)	2

Counts/frequency: Male (35, 64.8%), Female (19, 35.2%)

What is you age range? *(age)*

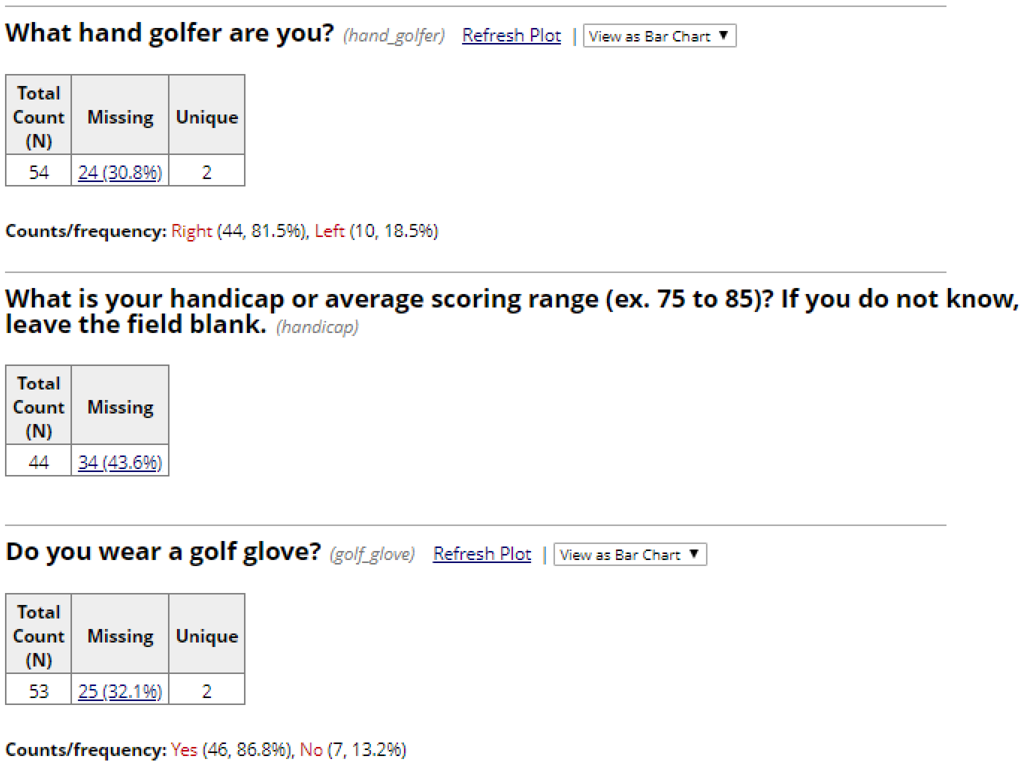
Total Count (N)	Missing	Unique
54	24 (30.8%)	4

Counts/frequency: 18-35 (21, 38.9%), 36-50 (8, 14.8%), 51-65 (17, 31.5%), 66+ (8, 14.8%)

What is your dominant hand? *(dominant_hand)*

Total Count (N)	Missing	Unique
54	24 (30.8%)	2

Counts/frequency: Right (50, 92.6%), Left (4, 7.4%)



What hand golfer are you? *(hand_golfer)*

Total Count (N)	Missing	Unique
54	24 (30.8%)	2

Counts/frequency: Right (44, 81.5%), Left (10, 18.5%)

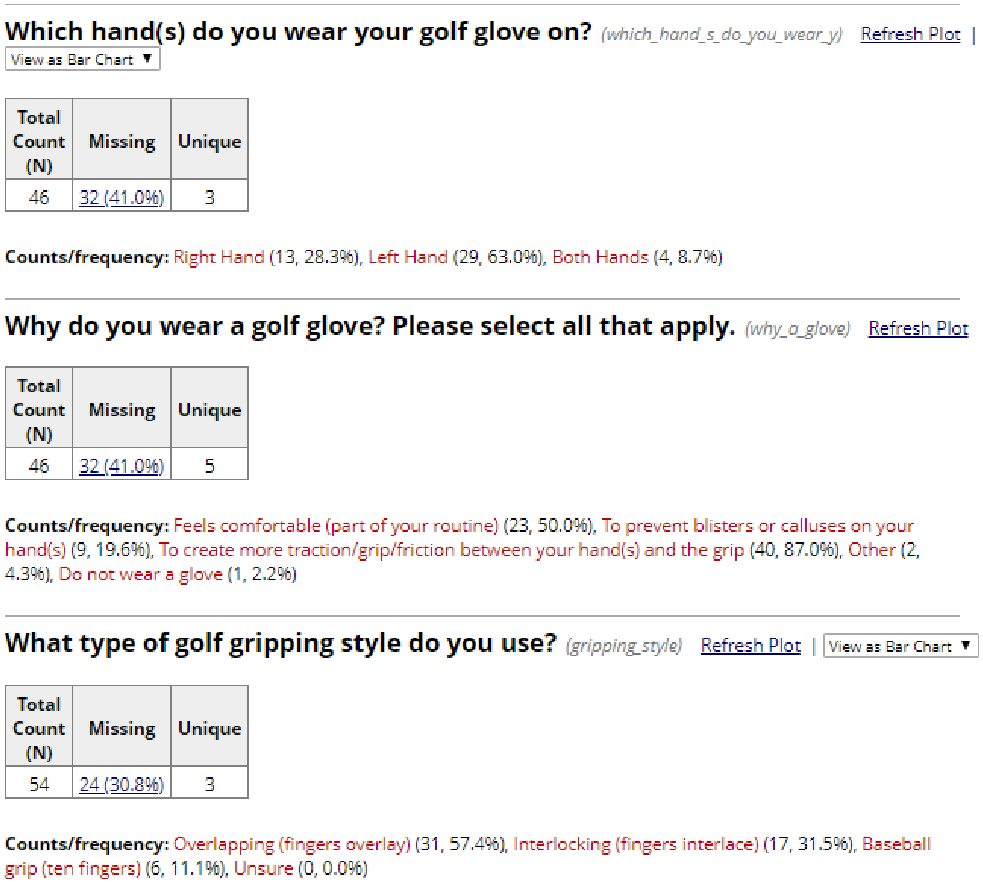
What is your handicap or average scoring range (ex. 75 to 85)? If you do not know, leave the field blank. *(handicap)*

Total Count (N)	Missing
44	34 (43.6%)

Do you wear a golf glove? *(golf_glove)*

Total Count (N)	Missing	Unique
53	25 (32.1%)	2

Counts/frequency: Yes (46, 86.8%), No (7, 13.2%)



Which hand(s) do you wear your golf glove on? *(which_hand_s_do_you_wear_y)*

Total Count (N)	Missing	Unique
46	32 (41.0%)	3

Counts/frequency: Right Hand (13, 28.3%), Left Hand (29, 63.0%), Both Hands (4, 8.7%)

Why do you wear a golf glove? Please select all that apply. *(why_a_glove)*

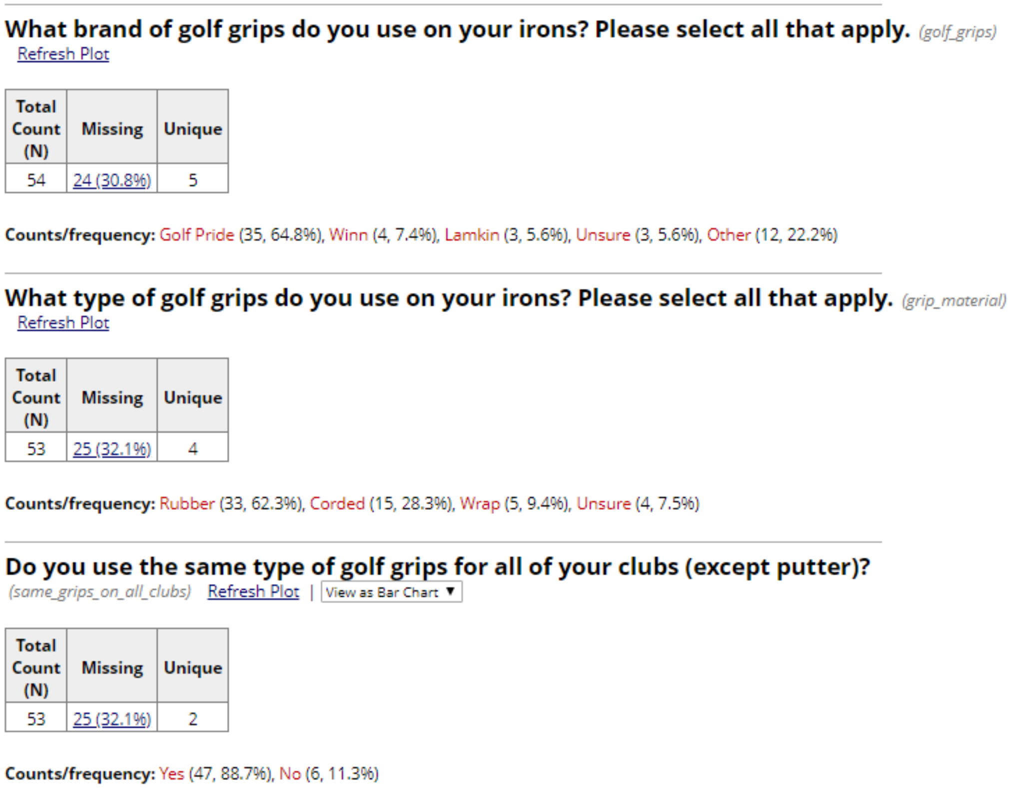
Total Count (N)	Missing	Unique
46	32 (41.0%)	5

Counts/frequency: Feels comfortable (part of your routine) (23, 50.0%), To prevent blisters or calluses on your hand(s) (9, 19.6%), To create more traction/grip/friction between your hand(s) and the grip (40, 87.0%), Other (2, 4.3%), Do not wear a glove (1, 2.2%)

What type of golf gripping style do you use? *(gripping_style)*

Total Count (N)	Missing	Unique
54	24 (30.8%)	3

Counts/frequency: Overlapping (fingers overlay) (31, 57.4%), Interlocking (fingers interlace) (17, 31.5%), Baseball grip (ten fingers) (6, 11.1%), Unsure (0, 0.0%)



What brand of golf grips do you use on your irons? Please select all that apply. *(golf_grips)*

Total Count (N)	Missing	Unique
54	24 (30.8%)	5

Counts/frequency: Golf Pride (35, 64.8%), Winn (4, 7.4%), Lamkin (3, 5.6%), Unsure (3, 5.6%), Other (12, 22.2%)

What type of golf grips do you use on your irons? Please select all that apply. *(grip_material)*

Total Count (N)	Missing	Unique
53	25 (32.1%)	4

Counts/frequency: Rubber (33, 62.3%), Corded (15, 28.3%), Wrap (5, 9.4%), Unsure (4, 7.5%)

Do you use the same type of golf grips for all of your clubs (except putter)? *(same_grips_on_all_clubs)*

Total Count (N)	Missing	Unique
53	25 (32.1%)	2

Counts/frequency: Yes (47, 88.7%), No (6, 11.3%)

If you answered no to the previous question, please explain why? *(why_not_the_same_grips)*

Total Count (N)	Missing
5	73 (93.6%)

What is the firmness of your golf grips on your irons? Please select all that apply.

(grip_firmness) Refresh Plot

Total Count (N)	Missing	Unique
52	26 (33.3%)	4

Counts/frequency: Hard (10, 19.2%), Medium (31, 59.6%), Soft (10, 19.2%), Unsure (5, 9.6%)

What is the size of your golf grips on your irons? Please select all that apply. *(grip_size)*

Refresh Plot

Total Count (N)	Missing	Unique
53	25 (32.1%)	4

Counts/frequency: Standard (40, 75.5%), Undersized (1, 1.9%), Mid-sized (12, 22.6%), Jumbo (2, 3.8%), Unsure (0, 0.0%)

How often do you re-grip your golf clubs? *(re_grip_clubs)* Refresh Plot | View as Bar Chart ▼

Total Count (N)	Missing	Unique
53	25 (32.1%)	4

Counts/frequency: Every season (once a year) (23, 43.4%), Every other season (once every two years) (16, 30.2%), Have not re-gripped my clubs (6, 11.3%), Other (8, 15.1%)

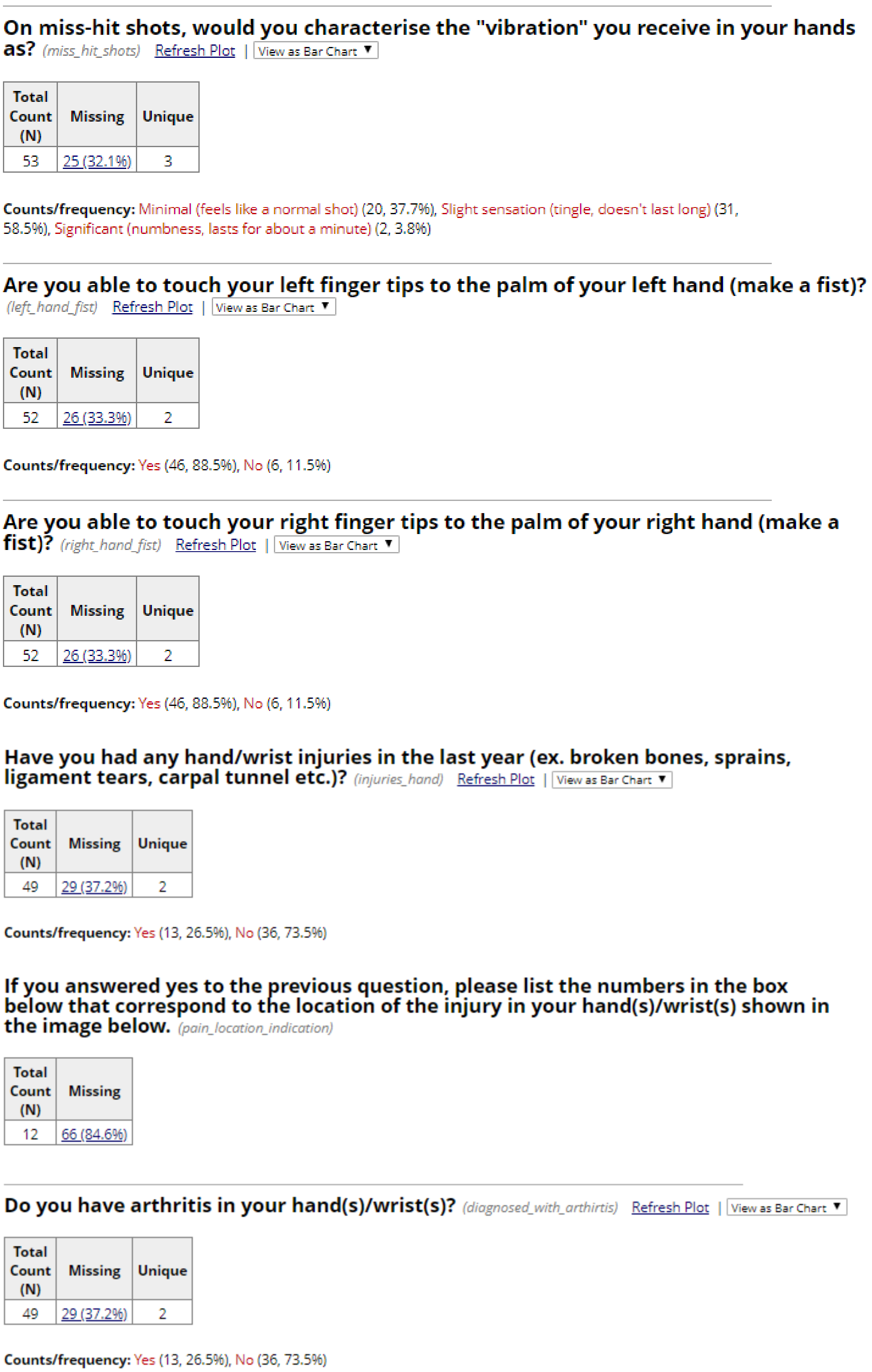
Do you find anything wrong or uncomfortable with your current golf grips on your irons? *(wrong_with_grips)* Refresh Plot | View as Bar Chart ▼

Total Count (N)	Missing	Unique
52	26 (33.3%)	2

Counts/frequency: Yes (6, 11.5%), No (46, 88.5%)

If you answered yes to the previous question, please explain why? *(why_to_previous_question)*

Total Count (N)	Missing
4	74 (94.9%)



On miss-hit shots, would you characterise the "vibration" you receive in your hands as? *(miss_hit_shots)* Refresh Plot | View as Bar Chart ▼

Total Count (N)	Missing	Unique
53	25 (32.1%)	3

Counts/frequency: Minimal (feels like a normal shot) (20, 37.7%), Slight sensation (tingle, doesn't last long) (31, 58.5%), Significant (numbness, lasts for about a minute) (2, 3.8%)

Are you able to touch your left finger tips to the palm of your left hand (make a fist)? *(left_hand_fist)* Refresh Plot | View as Bar Chart ▼

Total Count (N)	Missing	Unique
52	26 (33.3%)	2

Counts/frequency: Yes (46, 88.5%), No (6, 11.5%)

Are you able to touch your right finger tips to the palm of your right hand (make a fist)? *(right_hand_fist)* Refresh Plot | View as Bar Chart ▼

Total Count (N)	Missing	Unique
52	26 (33.3%)	2

Counts/frequency: Yes (46, 88.5%), No (6, 11.5%)

Have you had any hand/wrist injuries in the last year (ex. broken bones, sprains, ligament tears, carpal tunnel etc.)? *(injuries_hand)* Refresh Plot | View as Bar Chart ▼

Total Count (N)	Missing	Unique
49	29 (37.2%)	2

Counts/frequency: Yes (13, 26.5%), No (36, 73.5%)

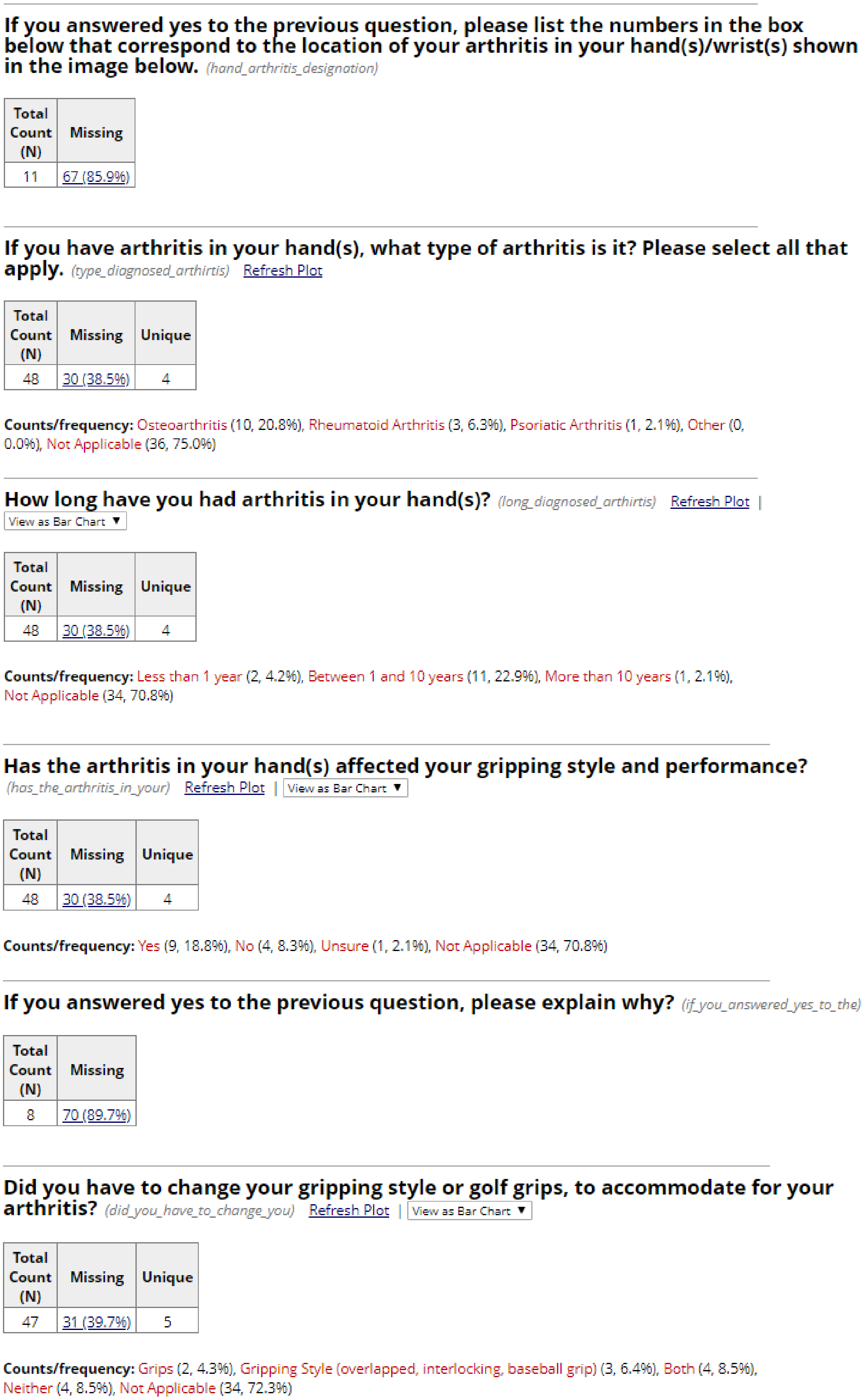
If you answered yes to the previous question, please list the numbers in the box below that correspond to the location of the injury in your hand(s)/wrist(s) shown in the image below. *(pain_location_indication)*

Total Count (N)	Missing
12	66 (84.6%)

Do you have arthritis in your hand(s)/wrist(s)? *(diagnosed_with_arthirtis)* Refresh Plot | View as Bar Chart ▼

Total Count (N)	Missing	Unique
49	29 (37.2%)	2

Counts/frequency: Yes (13, 26.5%), No (36, 73.5%)



If you answered yes to the previous question, please list the numbers in the box below that correspond to the location of your arthritis in your hand(s)/wrist(s) shown in the image below. *(hand_arthritis_designation)*

Total Count (N)	Missing
11	67 (85.9%)

If you have arthritis in your hand(s), what type of arthritis is it? Please select all that apply. *(type_diagnosed_arthirtis)* Refresh Plot

Total Count (N)	Missing	Unique
48	30 (38.5%)	4

Counts/frequency: Osteoarthritis (10, 20.8%), Rheumatoid Arthritis (3, 6.3%), Psoriatic Arthritis (1, 2.1%), Other (0, 0.0%), Not Applicable (36, 75.0%)

How long have you had arthritis in your hand(s)? *(long_diagnosed_arthirtis)* Refresh Plot | View as Bar Chart ▼

Total Count (N)	Missing	Unique
48	30 (38.5%)	4

Counts/frequency: Less than 1 year (2, 4.2%), Between 1 and 10 years (11, 22.9%), More than 10 years (1, 2.1%), Not Applicable (34, 70.8%)

Has the arthritis in your hand(s) affected your gripping style and performance? *(has_the_arthritis_in_your)* Refresh Plot | View as Bar Chart ▼

Total Count (N)	Missing	Unique
48	30 (38.5%)	4

Counts/frequency: Yes (9, 18.8%), No (4, 8.3%), Unsure (1, 2.1%), Not Applicable (34, 70.8%)

If you answered yes to the previous question, please explain why? *(if_you_answered_yes_to_the)*

Total Count (N)	Missing
8	70 (89.7%)

Did you have to change your gripping style or golf grips, to accommodate for your arthritis? *(did_you_have_to_change_you)* Refresh Plot | View as Bar Chart ▼

Total Count (N)	Missing	Unique
47	31 (39.7%)	5

Counts/frequency: Grips (2, 4.3%), Gripping Style (overlapped, interlocking, baseball grip) (3, 6.4%), Both (4, 8.5%), Neither (4, 8.5%), Not Applicable (34, 72.3%)

Would you buy new golf grips if they could have a positive influence on your game?

(would_you_buy_new_golf_gri)

Total Count (N)	Missing	Unique
49	29 (37.2%)	1

Counts/frequency: Yes (49, 100.0%), No (0, 0.0%)

Do you feel that improved golf grips could help individuals with hand arthritis?

(do_you_feel_that_improved)

Total Count (N)	Missing	Unique
49	29 (37.2%)	2

Counts/frequency: Yes (47, 95.9%), No (2, 4.1%)

Do you feel that the manufacture and development of golf grips can reduce unnecessary or potentially physically damaging "vibration" on miss-hit shots?

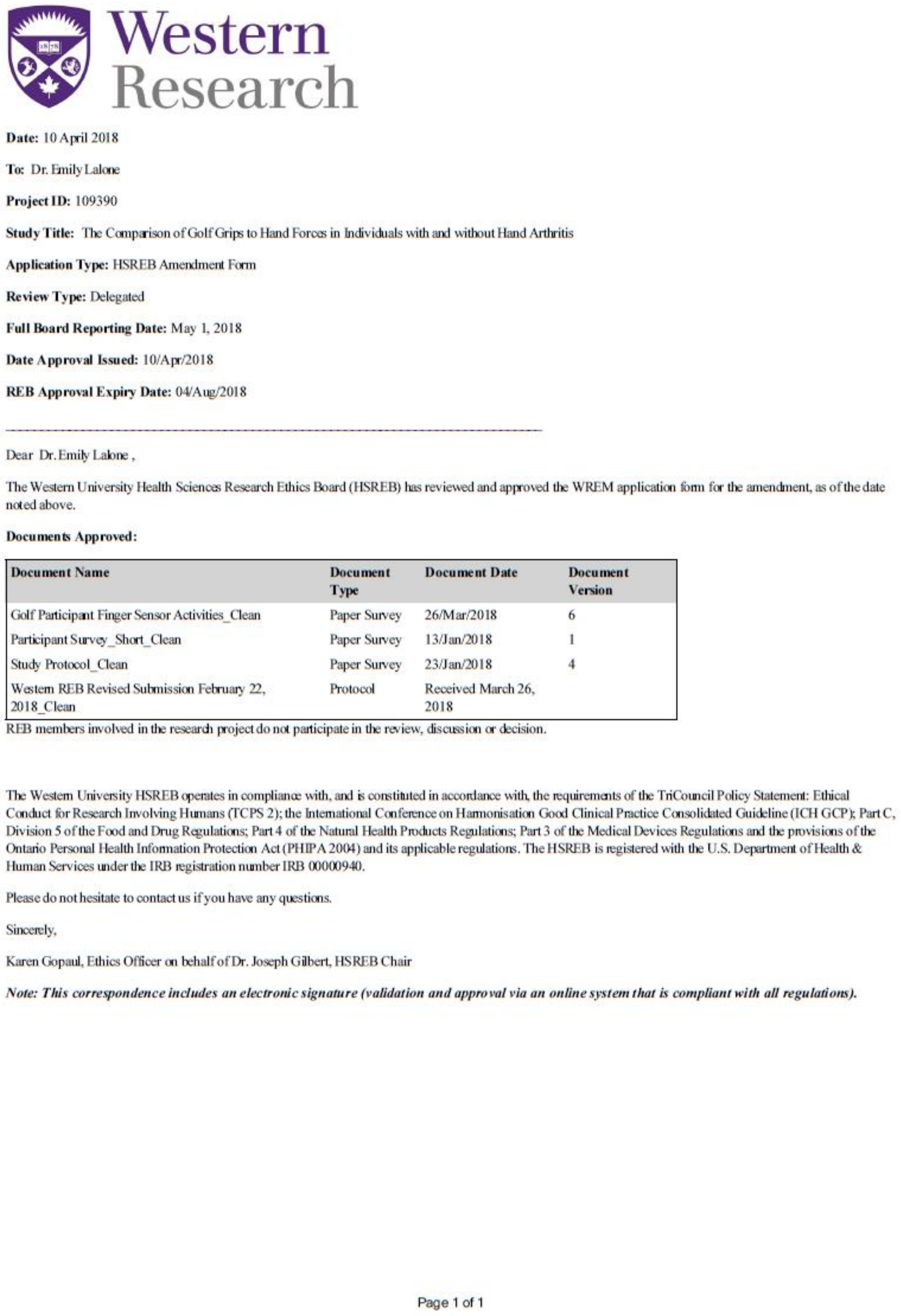
(do_you_feel_that_the_manuf)

Total Count (N)	Missing	Unique
49	29 (37.2%)	2

Counts/frequency: Yes (47, 95.9%), No (2, 4.1%)

Appendix G – Ethics Approval (Chapter 2)

The following appendices are the ethics approval that were obtained in order to conduct the studies described in Chapter 2 and 3.



Western Research

Date: 10 April 2018

To: Dr. Emily Lalone

Project ID: 109390

Study Title: The Comparison of Golf Grips to Hand Forces in Individuals with and without Hand Arthritis

Application Type: HSREB Amendment Form

Review Type: Delegated

Full Board Reporting Date: May 1, 2018

Date Approval Issued: 10/Apr/2018

REB Approval Expiry Date: 04/Aug/2018

Dear Dr. Emily Lalone ,

The Western University Health Sciences Research Ethics Board (HSREB) has reviewed and approved the WREM application form for the amendment, as of the date noted above.

Documents Approved:

Document Name	**Document Type**	**Document Date**	**Document Version**
Golf Participant Finger Sensor Activities_Clean	Paper Survey	26/Mar/2018	6
Participant Survey_Short_Clean	Paper Survey	13/Jan/2018	1
Study Protocol_Clean	Paper Survey	23/Jan/2018	4
Western REB Revised Submission February 22, 2018_Clean	Protocol	Received March 26, 2018	

REB members involved in the research project do not participate in the review, discussion or decision.

The Western University HSREB operates in compliance with, and is constituted in accordance with, the requirements of the TriCouncil Policy Statement: Ethical Conduct for Research Involving Humans (TCPS 2); the International Conference on Harmonisation Good Clinical Practice Consolidated Guideline (ICH GCP); Part C, Division 5 of the Food and Drug Regulations; Part 4 of the Natural Health Products Regulations; Part 3 of the Medical Devices Regulations and the provisions of the Ontario Personal Health Information Protection Act (PHIPA 2004) and its applicable regulations. The HSREB is registered with the U.S. Department of Health & Human Services under the IRB registration number IRB 00000940.

Please do not hesitate to contact us if you have any questions.

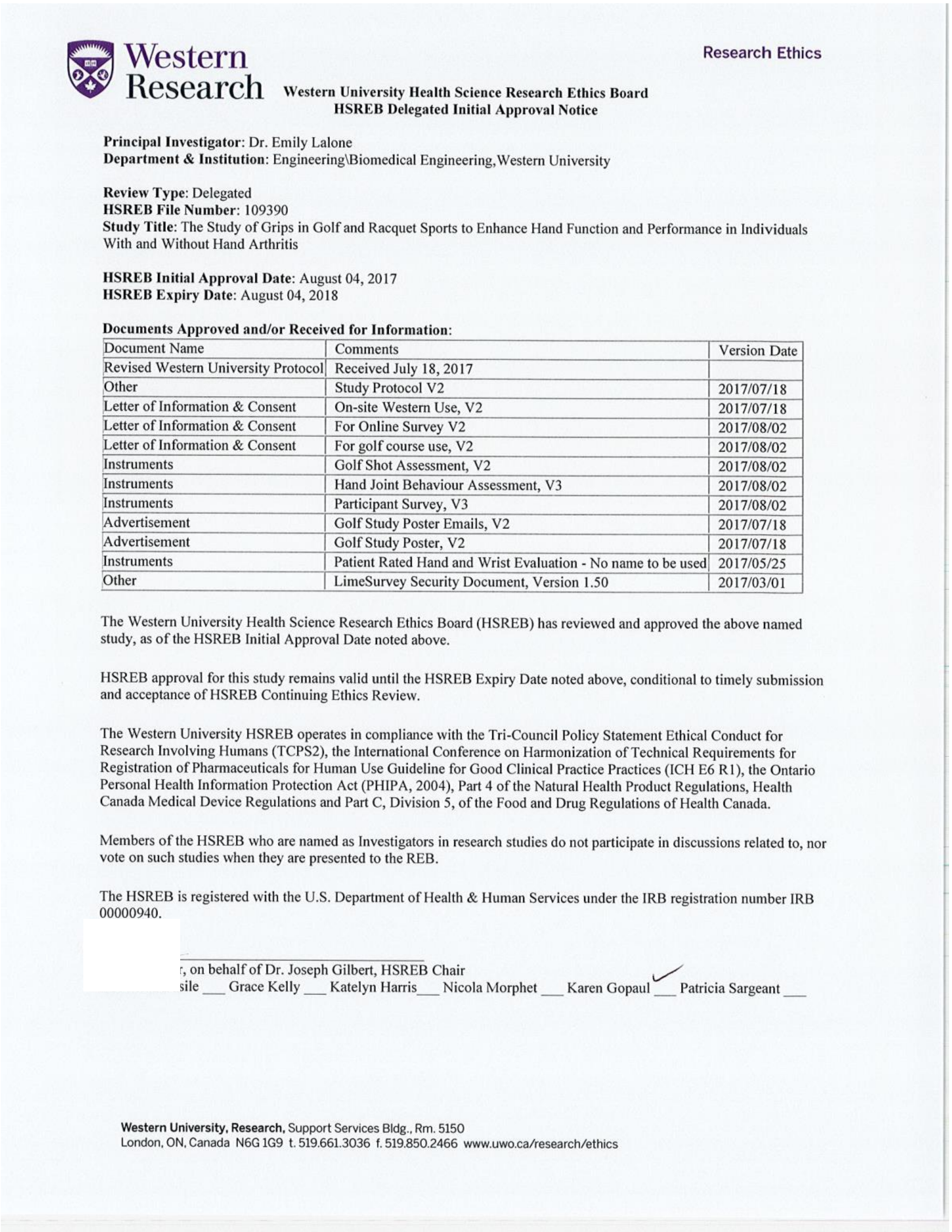
Sincerely,

Karen Gopaul, Ethics Officer on behalf of Dr. Joseph Gilbert, HSREB Chair

Note: This correspondence includes an electronic signature (validation and approval via an online system that is compliant with all regulations).

Page 1 of 1

Appendix H – Ethics Approval (Chapter 3)



Western Research

Research Ethics

Western University Health Science Research Ethics Board
HSREB Delegated Initial Approval Notice

Principal Investigator: Dr. Emily Lalone
Department & Institution: Engineering\Biomedical Engineering,Western University

Review Type: Delegated
HSREB File Number: 109390
Study Title: The Study of Grips in Golf and Racquet Sports to Enhance Hand Function and Performance in Individuals With and Without Hand Arthritis

HSREB Initial Approval Date: August 04, 2017
HSREB Expiry Date: August 04, 2018

Documents Approved and/or Received for Information:

Document Name	Comments	Version Date
Revised Western University Protocol	Received July 18, 2017	
Other	Study Protocol V2	2017/07/18
Letter of Information & Consent	On-site Western Use, V2	2017/07/18
Letter of Information & Consent	For Online Survey V2	2017/08/02
Letter of Information & Consent	For golf course use, V2	2017/08/02
Instruments	Golf Shot Assessment, V2	2017/08/02
Instruments	Hand Joint Behaviour Assessment, V3	2017/08/02
Instruments	Participant Survey, V3	2017/08/02
Advertisement	Golf Study Poster Emails, V2	2017/07/18
Advertisement	Golf Study Poster, V2	2017/07/18
Instruments	Patient Rated Hand and Wrist Evaluation - No name to be used	2017/05/25
Other	LimeSurvey Security Document, Version 1.50	2017/03/01

The Western University Health Science Research Ethics Board (HSREB) has reviewed and approved the above named study, as of the HSREB Initial Approval Date noted above.

HSREB approval for this study remains valid until the HSREB Expiry Date noted above, conditional to timely submission and acceptance of HSREB Continuing Ethics Review.

The Western University HSREB operates in compliance with the Tri-Council Policy Statement Ethical Conduct for Research Involving Humans (TCPS2), the International Conference on Harmonization of Technical Requirements for Registration of Pharmaceuticals for Human Use Guideline for Good Clinical Practice Practices (ICH E6 R1), the Ontario Personal Health Information Protection Act (PHIPA, 2004), Part 4 of the Natural Health Product Regulations, Health Canada Medical Device Regulations and Part C, Division 5, of the Food and Drug Regulations of Health Canada.

Members of the HSREB who are named as Investigators in research studies do not participate in discussions related to, nor vote on such studies when they are presented to the REB.

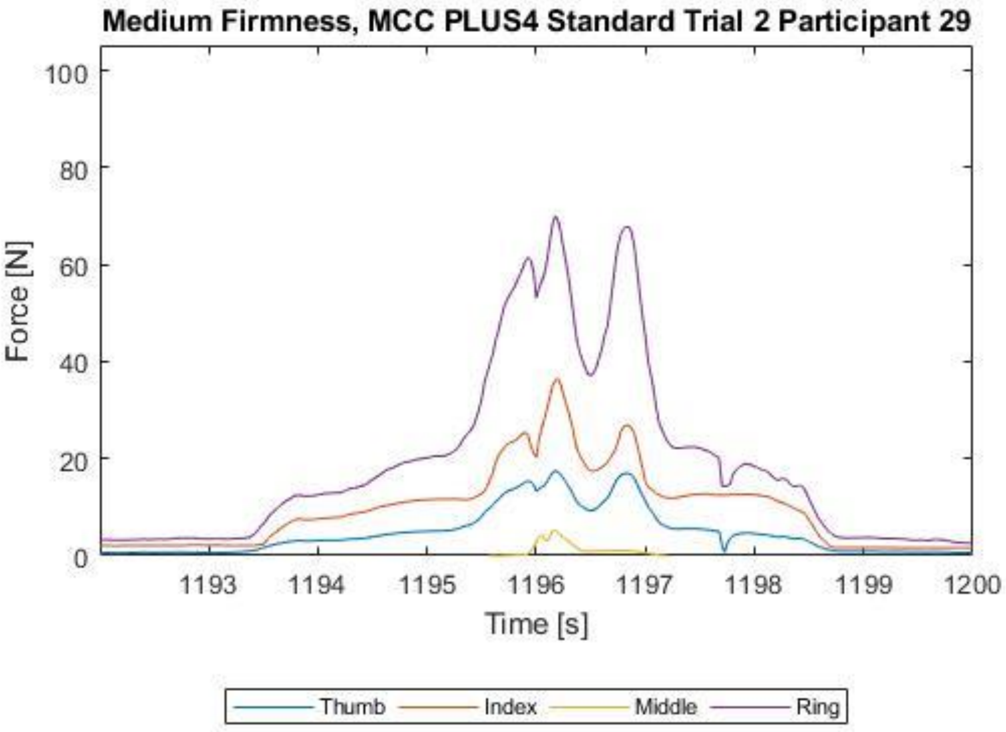
The HSREB is registered with the U.S. Department of Health & Human Services under the IRB registration number IRB 00000940.

[redacted], on behalf of Dr. Joseph Gilbert, HSREB Chair
___ Grace Kelly ___ Katelyn Harris___ Nicola Morphet ___ Karen Gopaul ✓___ Patricia Sargeant ___

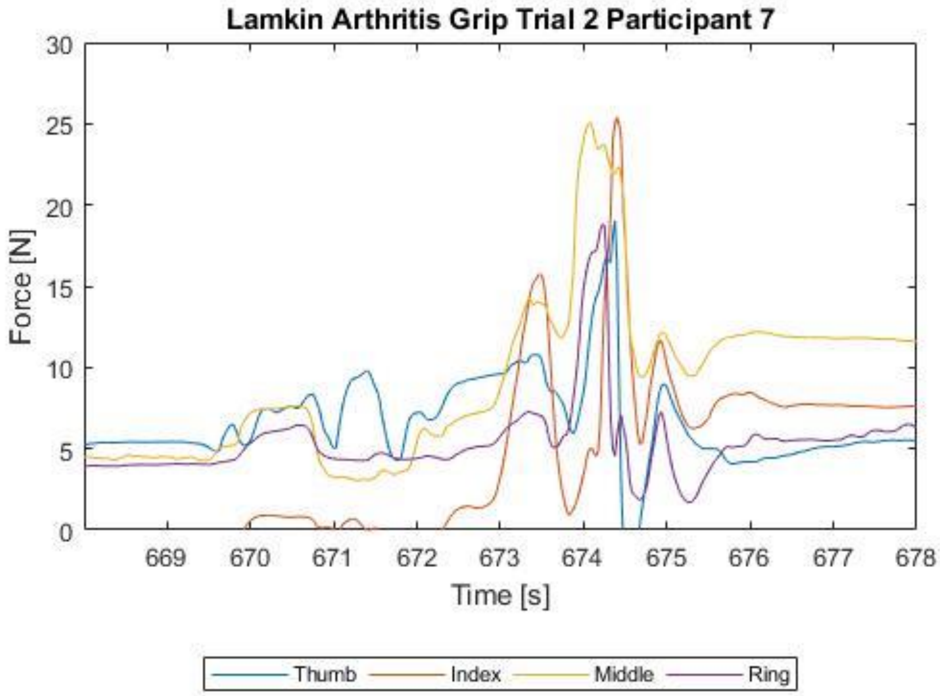
Western University, Research, Support Services Bldg., Rm. 5150
London, ON, Canada N6G 1G9 t. 519.661.3036 f. 519.850.2466 www.uwo.ca/research/ethics

Appendix I – Golf Grip Force Study Supplementary Information (Chapter 3)

I1. Golf Grip Force Graph for Participant 29 (healthy female participant) for the Medium Firmness, Standard Diameter (MCC PLUS4) Golf Grip Design



I2. Golf Grip Force Graph for Participant 7 (healthy female participant) for the Lamkin Arthritis Golf Grip Design

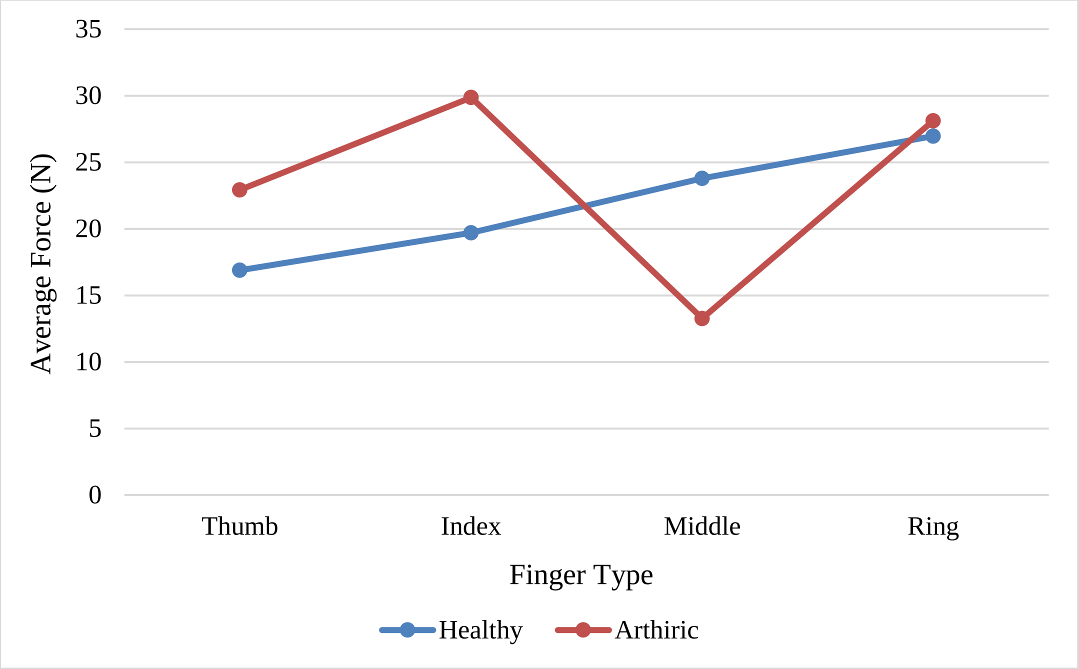


I3. With and Without the Latex Finger Cots Evaluation (paired sample t-test)

With and Without Latex Finger Cots	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference		Sig. (2-tailed)
			Lower	Upper	
Thumb	13.3	3.4	-5.5	9.2	0.6
Index	70.5	18.2	-75.3	2.7	0.07
Middle	6.4	1.6	-0.7	6.4	0.01
Ring	1.3	0.6	-1.4	1.9	0.07

I4. MCC PLUS4 Standard Grip Average Individual Finger Force

Note: The chart below demonstrates the average finger force magnitude of the bottom gripping hand thumb, index, middle, and ring finger when swinging with the MCC PLUS4 standard golf grip for the healthy participants and participants with hand arthritis.



Appendix J – Curriculum Vitae

Sara Holland

EDUCATION

M.E.Sc. Mechanical and Materials Engineering *(May 2017-May 2019)*
Western University (London, ON)
B.E.Sc. 2017, Mechanical and Materials Engineering *(September 2013-April 2017)*
Western University (London, ON)

WORK EXPERIENCE

Project Coordinator Role: ES 1050 Redesign Team *(January 2018-April 2019)*
The Department of Electrical and Computer Engineering
Western University (London, ON)
Graduate Teaching Assistant *(September 2017-April 2018/September 2018-April 2019)*
Foundations of Engineering Practice ES 1050
Western University (London, ON)
Western Engineering Summer Academy Instructor *(August 2018)*
Summer Student Position
Western University (London, ON)
Graduate Research Assistant *(May 2017-May 2019)*
Mechanical and Materials Engineering
Western University (London, ON)

ACTIVITIES AND ACHIEVEMENTS

Western Graduate Research Scholar (WGRS) *(May 2017-April 2019)*
Mechanical and Materials Engineering
Western University (London, ON)
Supervisor for Volunteers, Work Study, and Summer Students *(May 2017-April 2019)*

PRESENTIONS AT LOCAL CONFERENCES

- Holland, S. (June 2019). "How to Get a Better Grip on Your Golf Game." Health Science/Biomedical Engineering Collaboration Research Day, Western University, London, On, Canada. (Presentation).
- Holland, S., Dickey, J., Ferreira, L., and Lalone, E. (June 2019). Assessing Hand Force and Grip Configuration Variability in Golfers with and without Hand Arthritis. Proceedings of The Joint Canadian Society for Mechanical Engineering and CFD Society of Canada International Congress 2019, London, On, Canada. (Podium Presentation).
- Holland, S., Dickey, J., Ferreira, L., and Lalone, E. (April 2019). The Comparison of Golf Grips to Hand Forces in Individuals with and without Hand Arthritis. London Health Research Day, London Convention Centre, London, Ontario, CA. (Poster).
- Holland, S., Dickey, J., Ferreira, L., and Lalone, E. (March 2019). Golf Grip Force

Evaluation in Individuals with and without Hand Arthritis Using a New Wearable Sensor Technology. Western Research Forum 2019, Western University, London, Ontario, CA. (Key Note Speaker).

- Holland, S., Dickey, J., Ferreira, L., and Lalone, E. (March 2019). Investigating the Hand Forces Produced while Golfing Using a New Wearable Sensor Technology in Individuals with and without Hand Arthritis. The 16th Annual Ontario Biomechanics Conference, Allister, Ontario, CA. (Poster).
- Holland, S., MacDermid-Watts, K., Dickey, J., Ferreira, L., and Lalone, E. (May 2018). Evaluating the Hand Forces in Individuals with and without Hand Arthritis using a New Wearable Sensor Technology. The 3rd Biennial Canadian Bone and Joint Conference, Western University, London, Ontario, CA. (Poster).
- Holland, S., Dickey, J., Ferreira, L., and Lalone, E. (May 2018). Comparison of Golf Grips to Hand Forces in Individuals with and without Hand Arthritis. London Health Research Day, London Convention Centre, London, Ontario, CA. (Poster).
- Holland, S., Dickey, J., Ferreira, L., and Lalone, E. (March 2018). Comparison of Golf Grips to Hand Forces in Individuals with and without Hand Arthritis. The 2nd Biennial Inspiring Young Women in STEM Conference, Western University, London, Ontario, CA. (Poster).
- Holland, S., Riddle, M., Dickey, J., Ferreira, L., and Lalone, E. (October 2017). Comparison of Golf Grips to Hand Forces in Individuals with and without Hand Arthritis. The Arthritis Society Canada Tour 2017, St. Joseph's Health Care, London, Ontario, CA. (Poster).
- Holland, S., Dickey, J., Ferreira, L., and Lalone, E. (August 2017). Comparison of Forces in Various Golf Grips to Individuals with and without Hand Arthritis. The Collaborative Training Program Summer Student Research Symposium in Musculoskeletal Health Research, Western University, London, Ontario, CA. (Podium).

PEER REVIEW PUBLUCATIONS

- Riddle, M., MacDermid, J., Holland, S., Lalone, E., and Ferreira, L. (July 2018). Wearable Strain Gauge Based Technology Measures Manual Tactile Forces during Activities of Daily Living. The *Journal of Rehabilitation and Assistive Technologies Engineering,* epub ahead of print. (Publication).

ABSTRACTS AT NATIONAL AND INTERNATIONAL CONFERENCES

- Holland, S., Straatman, L., Sinden, K., and Lalone, E. (June 2019). Grip Configuration in People With and Without Hand Osteoarthritis During Tasks of Daily Living: Application of Dartfish Analysis Software. International Combined Orthopaedic Research Society (ICORS) 2019, Montreal, Quebec, CA. (Poster).
- Holland, S., Straatman, L., Robinson, S., Dickey, J., Ferreira, L., and Lalone, E. (September 2018). Investigation of Hand Forces Produced While Playing Golf: With the Use of New Wearable Sensor Technology to Assist in the Hand Function of Patients with and without Hand Arthritis. The 6th International Congress on Sport Science Research and Technology Support, Seville, Spain. (Podium).
- Holland, S., Straatman, L., Robinson, S., Dickey, J., Ferreira, L., and Lalone, E. (August

2018). Evaluating The Hand Forces in Individuals with and without Hand Arthritis using a New Wearable Sensor Technology in Golfers. The 20th Biennial Meeting of the Canadian Society for Biomechanics, Halifax, Nova Scotia, CA. (Poster).

- Holland, S., MacDermid-Watts, K., Dickey, J., Ferreira, L., and Lalone, E. (May 2017). Assessing Individuals with and without Hand Arthritis to Track the Hand Forces Produced Using a New Wearable Sensor Technology while Playing Golf. The 24th Canadian Connective Tissue Conference, The University of Toronto, Toronto, Ontario, CA. (Poster).
- Holland, S., Lalone, E., and MacDermid, J. (March 2018). Motion Demands of Tasks of Daily Life in People with Hand Osteoarthritis: Application of Dartfish Movement Analysis Software. The annual meeting of the Orthopedic Research Society, New Orleans, LA, USA. (Poster).

CONFERENCE PROCEEDING PUBLICATIONS

- Holland, S., Straatman, L., Robinson, S., Dickey, J., Ferreira, L., and Lalone, E. (September 2018). Investigation of Hand Forces Produced While Playing Golf: With the Use of New Wearable Sensor Technology to Assist in the Hand Function of Patients with and without Hand Arthritis. The 6th International Congress on Sport Science Research and Technology Support, Seville, Spain. (Conference Proceeding).

PROFESSIONAL DEVELOPMENT

- Collaborative Musculoskeletal Health Research (CMHR) Trainee, Western University, *September 2017-August 2019*
- Ivey Workshop: “Introduction to Strategy” presented by Dr. Michael Rouse, *May 2019*
- Ivey Workshop: “Future of Health Systems” presented by Dr. Zayna Khayat, *November 2018*
- Ivey Health Workshop: The Art and Science of Networking: Finding Your Tribe with Mira Ratkaj, Western University, *August 2018*
- Ivey Workshop: Small and Medium Enterprises – Building the Case for Commercialization and Venture Capital Investment with Dr. Brent Norton, Western University, *September 2017*
- Western University, Teaching Assistants Training Program, *June 2017*
- WORLDiscoveries Patent Search Workshop, Western Research Park, *June 2017*

VOLUNTEER WORK

ENGSquad: Just for Girls Mentorship Program *(May 2018 and May 2019)*
Volunteer and Demonstrator
Western University (London, ON)
Discovery Day *(May 2019)*
Volunteer
Western University (London, ON)
Canadian Engineering Accreditation Board (CEAB) Review *(November 2018)*
Graduate Teaching Assistant (GTA) Participant
Western University (London, ON)

The Bone and Joint Institute External Review *(November 2018)*
Trainee Participant
Western University (London, ON)
Mechanical and Materials Engineering Graduate Research Social *(November 2018)*
Graduate Student Participant
Western University (London, ON)
The Sunningdale Teaching Academy Junior Golf Camp *(July 2018)*
Volunteer and Teacher
Sunningdale Golf and Country Club (London, ON)
The Early Outreach Conference (REACH) *(May 2017 and May 2018)*
Volunteer and Demonstrator
Western University (London, ON)
28th Annual Children's Health Foundations Golf Classic Family Tournament *(July 2017)*
Volunteer
Sunningdale Golf and Country Club (London, ON)