MEASUREMENT OF THE MAXIMUM REACH ENVELOPE IN PERSONS WITH AND WITHOUT SHOULDER INJURY

by

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With great thanks to:

My parents who support me and remind me that
"Everything happens for a reason"
&
The inspiring mentors who have guided me.

"I have no special talents; I am only passionately curious"
Albert Einstein

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ABSTRACT

BACKGROUND: The maximum reach envelope (MRE) is a volumetric measure of space used to describe the dimension of upper extremity movement (Maynard 1934). The MRE has been used in ergonomics for measurement and design of workstations. With primary movement at the glenohumeral joint, it has potential applications in clinical assessment.

OBJECTIVES: This research will measure and quantify the MRE on a novel group. The objectives are to measure and compare a loaded MRE between the following samples: asymptomatic young, and older adults; asymptomatic and symptomatic complete tear rotator cuff individuals; and to develop the analytical techniques in comparing maximum reach envelopes.

PROPOSED METHODS: Clinical measures, and three dimensional MRE measurements from will be recorded for persons with asymptomatic and symptomatic (rotator cuff tear) shoulders. Loads of 0, 0.5 and 1.0 Kg will be incorporated onto the MRE. Coordinate systems (cylindrical and spherical) and methods of analyses will be compared in determining differences between the MRE.

Keywords: Maximum Reach Envelope, Hand-held Loads, Shoulder, Rotator Cuff Tears, 3-D Kinematics

LIST OF ABBREVIATIONS USED

CPSAM: Computerized Potentiometric System for Structural and Anthropometric Measures

DASH: Disabilities of the Arm, Shoulder and Hand Survey

ICF: International Classification of Function

MRE: Maximum Reach Envelope

PRU : Primary Recording Unit

ROM: Range of Motion

WORC: Western Ontario Rotator Cuff Survey

CHAPTER 1 INTRODUCTION

Reach is a human movement requiring strength and mobility of the upper extremity. It is a common functional movement in many occupations and activities of daily life. Whether simplistic or complex in nature, reaching movements are frequent and necessary in workplaces such as a checkout stand, assembly line or driving a vehicle. However, research regarding functionally dynamic reach measurement and factors that affect reach is still evolving. The aim of the current research is to address some of the limitations of reach measurement and determine a method of quantifying the reaching motion of the upper limb. The secondary aim is to develop a measurement process of the MRE relevant to both ergonomic and clinical applications.

In biomechanical and ergonomic investigations, reasons for quantifying and measuring human movement include increasing productivity, prevention of injury, and rehabilitation. The proposed method of measuring the gross movement of reach is the use of a reach envelope. The maximum reach envelope (MRE) is a term defined in engineering and ergonomics literature that encompasses the volume of space accessed by a touch, pinch, or grip action of the upper limb (Maynard, 1934). Previously used in workspace measurement and design, the maximum reach envelope provides an outer limit for where tools or tasks should be placed with respect to a person. The maximum reach envelope typically involves movement of an extended upper limb executed about the shoulder joint (Sengupta & Das, 2000). As such, the maximum reach envelope has applications within workspace design, and from a clinical perspective, it may further the understanding of functional limitations and shoulder mobility.

The glenohumeral joint is the point of rotation for many fundamental movements of the upper extremity angular motions such as flexion, extension, internal and external

rotation, and abduction/adduction. Combinations of these motions are usually required for successful completion of reaching tasks. The glenohumeral has many degrees of freedom owing to its ball and socket design resulting in a large overall range of motion for the upper limb (Omoumi et al., 2011). However, with a large range of motion, the glenohumeral joint has an increased risk for dislocation and instability, challenging clinical treatment and classification. A prevalent injury at the shoulder joint is a rotator cuff tear. Dislocations of the humeral head from the glenoid capsule are seen due to minimal skeletal restraints and overall structure of the shoulder capsule placing demands upon the rotator cuff muscle group. These tears, along with other shoulder injuries are the second leading workplace injury in the Atlantic Region next to disorders of the low back (WCB of Nova Scotia, 2015). The shoulder is also the 3rd highest affected joint for osteoarthritis. The current combination of occupational injury and degenerative disease related rotator cuff pathologies presents a need for research in prevention, treatment and rehabilitation of the glenohumeral joint. There are large wait times for surgery, and as a result, some people may spend over a year with an injury that impacts their functional reach. Identifiable differences in the reach of persons with shoulder injury may better describe their functional ability in occupations and/or activities of daily life.

Current assessments of shoulder function are completed in the diagnosis, and intervention phases of shoulder injury. These assessments encompass the range of motion of the joint along with other pertinent clinical measures. These clinical measures include measures of pain, strength and a gross classification of function. Incorporating patient questionnaires, such as the Western Ontario Rotator Cuff Index (WORC), The disabilities of the Arm, Shoulder and Hand Outcome (DASH) and The Veterans Rand 12 Health Survey (VR-12) are other methods of determining shoulder function. These measures aim

to give greater understanding as to the level of disability each individual may be experiencing.

1.1 Statement of Research Objectives

Currently there is no gold standard in the ergonomics literature for upper limb functional assessment, thus the overall goal of this research is to focus on a comparison of the MRE in asymptomatic individuals and symptomatic with a full thickness rotator cuff tear. This will serve as a feasibility study, to determine if this measurement can be obtained and used in individualized and group comparisons. In order to compare the reach envelope within and between groups, a non-commercialized three-dimensional motion capture device will be evaluated as a comprehensive tool providing the MRE measurement. This thesis will address the following measurement objectives:

1. Compare the use of two coordinate systems (cylindrical and spherical coordinates) in describing and representing the MRE;
2. Investigate the effectiveness of univariate and multivariate analyses in determining differences between and within the MRE of differing groups;
    a. Perform a proof in principle analysis of methods to quantify the MRE for clinical assessment.
3. Compare the effect of external loads on the maximum reach envelope of 3 subject groups: young asymptomatic, age-matched asymptomatic, and symptomatic (rotator-cuff tear).

This study will expand upon previous methodology used to measure functionally dynamic reach envelopes of an asymptomatic sample of adults (Kozey & Das, 2002; Johnston et Dewis, & Kozey, 2016; Sengupta & Das, 2000). A comparative analysis will evaluate methods of modeling reach using a three dimensional motion capture device.

The primary outcomes include: maximum reach envelopes in both asymptomatic individuals and those with diagnosed full thickness rotator cuff tears using three dimensional kinematics. Participants will be assessed with no load and also with loads of 0.5 Kg and 1.0 Kg.

It will be necessary to first establish analytic methods (quantification and data dissemination) for the MRE to address comparative objectives. It is hypothesized that there will be identifiable differences in the overall reach envelope of the participant samples, along with characteristic patterns within the envelopes. There will be a significant difference in the reach envelope between young and older adult asymptomatic samples. Similarly, there will be a difference between the reach envelope of the asymptomatic and symptomatic samples. There will be an overall effect of load on all subject samples, as was seen previously in a young asymptomatic sample (Johnston, Dewis & Kozey, 2016). These measured effects and patterns will create meaningful results that can provide a preliminary measure of reach to be used in future assessment endeavors. These results will be successively applicable to workspace design and with greater understanding of load and injury.

1.2 Relevance and Scope of the Current Study

From a movement analysis perspective, the measurement of the lower limb is more advanced than that of the upper limb. In comparison, gait analysis of the lower limb provides a functional assessment of walking or running with a wealth of literature to support and compare results to. Since the upper limb does not have this wealth of understanding, there are implications of this research in multiple domains. This research will bridge the gaps between health research, engineering ergonomics and clinical assessment. The International Classification Framework as laid out by the World Health

Organization provides a useful model in understanding the potential implications of this research (WHO, 2001). Figure 1 displays an adapted model of the ICF framework for shoulder injury, displaying some of the underlying factors, implications, and routes for intervention. Every discipline (clinical, kinesiology) provides useful information regarding reach and mobility, and when united, research becomes reality and can promote change. Using this adapted framework, this research can be approached with an interdisciplinary lens that will target as many outcomes as possible. Potential implications of furthering reach understanding and shoulder movement include: ergonomic design, anatomical understanding, injury assessment, injury treatment, and methodologies. The end products of this research will include a comprehensive measurement and assessment tool for reach, and descriptive information regarding the reaching capabilities of individuals with and without shoulder injury (rotator cuff tears).

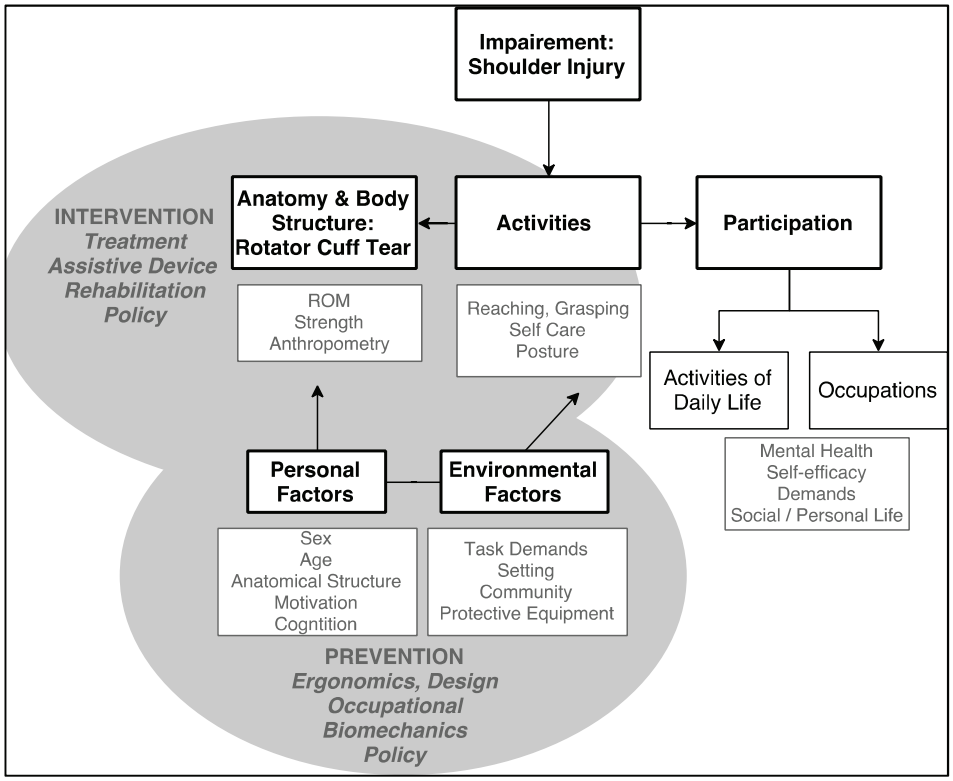


Figure 1 Adapted ICF model for shoulder injury

CHAPTER 2 REVIEW OF THE LITERATURE

As measurement of reach and upper limb movements is still evolving, there have been a variety of approaches to provide representative models of reach. The measurement of reach should be of enough reliability and validity to provide sound measures for design or clinical purposes. A review of existing literature regarding reach and reach envelopes presents the breadth of knowledge regarding reach primarily from an ergonomics perspective. However, there are certain measurement properties of reach that are applicable in the health research domain. Acknowledging the advancement of reach measurement in industrial and engineering settings encourages future development in clinical settings involving upper extremity injury.

2.1 Reach Envelopes

The reach envelope, by definition, encompasses the volume of space accessed by a touch, pinch, or grip action (Farley 1955; Konz & Goel, 1969; Maynard, 1934). Used in workspace measurement and design, the reach envelope provides an outer limit for where tools should be placed or where tasks should be performed with respect to a worker. To improve productivity and decrease risk of injury, the reaching tasks should not place large demands onto a person. The reach envelope has been mapped into three profiles including: normal, maximum and extreme reach. The normal reach area documented by Farley (1955), and Faulkner and Day (1970) is the area where most tasks are performed in, requiring primary movement at the elbow joint. In this area, the activity of the role of musculature of the shoulder and upper arm is minimal placing more demand on the forearm (Faulkner & Day, 1970). The authors highlighted that this area was a planar measurement of the workspace unlike the maximum and extreme volumes. The maximum reach envelope (MRE) adds the three dimensional component to the reach

measure and enlarges it to movement incorporating the shoulder joint. With movement performed at the shoulder joint while maintaining a stationary trunk, this envelope provides the outer limits of the volume in which tasks should be placed (Sengupta & Das, 2000). The MRE has been of great interest in workspace design as it provides a boundary for manual control and task placement (Chaffin et al., 2000). Movement incorporating trunk movement during reach is further defined as the extreme reach envelope, an area that is infrequently used for tasks, but may be required in certain occupations.

2.2 Measurement of Reach Envelopes

This study will focus on a measurement device known as CPSAM, a Computerized Potentiometric System for Anthropometric Measures (Das, Kozey & Tyson, 1994). It is a three dimensional motion capture system utilizing principles of linear algebra and an electromechanical device to record real time positions. Further explanation of this device will be explained later but it should be recognized that measuring the reach envelope has evolved since its beginnings in 1934.

The measurement of reach has progressed from simple planar measures towards complex mathematical modeling. The difficulty in measuring and recording reach is the fact that dynamic functional reach requires many postural adjustments from the upper limb and surrounding anatomical structures. Reach measures and methodologies have adapted to record reach as a fluid dynamic movement rather than a discrete movement.

The human reach envelope did not begin as a full volumetric measure. A general assumption of all reach measurements held both in past and current research was that the left arm mirrors the right arm in reach, and therefore data was only ever collected on the right side (Konz & Johnson, 2000). Maynard (1934) first described workspace layouts through measurement of reaching in horizontal and vertical planes. In this study, the

normal and maximum reach areas were traced as an outline when a person reached to sweep across a surface. Tracing reach in these planes, it was determined that in order to create a suitable workspace area for accommodating groups of workers, cutoff dimensions were needed. Percentiles of the reach (5^{th}, 50^{th} and 95^{th}) were used as these dimensions. However, in designing for the 50^{th} percentile or the "average" person, there would still be a large amount of people who would not be able to reach the full workspace. The 5^{th} percentile representing the smallest reach of the sample versus the largest percentile in 95^{th} could capture a larger target audience.

The automobile and aircraft industries were leaders in reach measurement development. In the development of interior layout of vehicles, these industries sought methods of three dimensional measurements. Cockpit layout and clearance was based on reach measurements that were recorded using wooden arc systems. In 1978, Kennedy pioneered the use of reach envelopes in aircraft cockpit design. Using a working sample of military pilots, the reach envelope was mapped in three-dimensional space using a wooden boom and arc system (a rod of wood rotating about an arc) that allowed the subject to push staves away from their body in varying planes and angles (Kennedy, 1978). These reach measurements were made relative to a fixed seat reference point to address engineering design. With this system the 5^{th}, 50^{th} and 95^{th} percentile of a stationary reach envelope were recorded. The fifth percentile was one of the most useful measures recorded in this study as in theory, 95 % of the user sample should have been able to reach to it (Kennedy, 1978).

Many of the highlighted methods of the introductory years of reach analysis were two dimensional and did not reflect the dynamic nature and capability of human

movement. Advances in technology have led to motion analyses in three dimensional space.

Das, Kozey, and Tyson (1994) developed a computerized potentiometric system for structural and anthropometric measures (CPSAM) as a simple and effective reach measurement tool. This system was able to determine a location of an unknown point in three dimensional space produced during reaching motions. A voltage change from a set of 4 potentiometers, a stylus attached with strings to the system was the initial recorded (Kozey, Das, & Tyson, 1994). Unknown positions in space were determined from the change in the voltage when the system's stylus was moved. For an estimated X, Y, and Z Cartesian coordinate of an unknown point the average absolute error associated with the system was 5, 6, and 3 mm respectively (Kozey, Das, & Tyson, 1994). The associated error was deemed acceptable for the use of measuring functional reach. A schematic of this system from Kozey and colleagues (1994) is available in Appendix A.

Sengputa and Das (2000) investigated seated and standing posture and its effects on the MRE. The study employed the previously mentioned CPSAM system created by Das and colleagues. Eighty participants, 40 male and 40 female, were recruited to perform a series of seated reach tasks using CPSAM. Their research advanced the collection methodology of the MRE. Participants held an upright posture with 2.5cm of spacing between the navel landmark and a table reference point for both seated and standing postures (Sengupta & Das, 2000). The maximum reach envelope was generated with a right arm motion and a pinch grip of the thumb, middle, and index fingers. The methodology was robust in capturing a large sample and addressing a posture constraint (sitting versus standing) common to many activities and workspaces. The analysis consisted of sectioning the reach envelopes into 7 horizontal planes and 14 angular

divisions which created defined regions. This sectioning of the reach envelope presented a novel, useful quantification method for future analyses.

Anthropometry has provided less demanding methods in modeling reach, in comparison to direct capture of reaching motions. Farley (1955) modeled the MRE as a simple sphere with a radius equal to the arm length of an industrial operator. This spherical model of reach has since been applied to reach measures. It was found as a fairly accurate technique in the center of the MRE, with an average error of 2 % in the area directly in front a person (Kozey & Mackenzie, 2002). However, it displayed greater error in the periphery of the sphere (Kozey & Mackenzie, 2002). Das and Behara (2008) also confirmed that arm length alone was not proportional to the magnitude of a reach distance. This research found a collection of anthropometrics measures that were directly related to modeling three dimensional reach (Das & Behara, 2008). Arm length was the most dominant, with stature, slump eye height, thigh clearance, forearm-hand length, shoulder height and shoulder slump height as other important measures. The measurement of the maximum reach envelope for an industrial workstation was revisited by Behara and Das using body dimensions and a further regression analysis in 2011. The time and difficulty of obtaining reach measures through physical collection was noted by the researchers hence the proposed anthropometric modeling method of maximum reach envelopes was developed (Behara & Das, 2011). The error from the estimated regression envelopes was ± 10%, which was deemed acceptable for the feasibility of the measurement (Behara & Das, 2011). These investigations highlighted the complexity of human anthropometry in determining reach.

While there may be debate between the feasibility of anthropometric modeling versus capturing reach motion, there is also the need to address functionality, cost and

time. Optical motion tracking systems are widely used in human kinematics. Through markers placed on the skin representing bony landmarks, camera systems can detect and track these marker positions through space. These systems can be very accurate in detecting human movement but hold some limitations that decrease applicability to upper limb motion analysis. For example, imaging, size and digitization decrease in accuracy as the volume of space in which data is collected increases (Rab, Petuskey, & Bagley, 2002). As reach movements are large and collected over a great volume there may be markers placed on anatomical parts such as the scapula that may not be visible when tracking the hand at the same time. The position of markers on anatomical landmarks also has raised concerns in the literature surrounding lower limb kinematics. Sagittal plane movements (flexion/extension) are well recorded well recorded in gait analysis (lower limb kinematics), however, rotational and frontal plan movements are often misrepresented (Benoit et al., 2008).

In comparing experimentally collected reach methods to those computed through anthropometrics, there are areas of caution that warrant further investigation. As body position, biomechanical and anatomical constraints have an effect on reach capabilities. Simply addressing reach models using anthropometrics should be approached with caution. Yet there are still computational, and missing data errors in experimentally collecting three dimensional motion capture. In summary, reach has long evolved from a two dimensional measure. However, there are tradeoffs with the collection methodology used to measure and interpret reach.

2.3 Factors Affecting Reach

Reach is dependent on the intrinsic and extrinsic factors acting on the human and environment. As clearly stated in the literature, small postural adjustments such as being seated versus standing or restricting movement at the elbow, deform the typical reach envelope. Similarly, to other anthropometric measures, it can be difficult to generalize a norm for all participants.

Design applications have displayed how external factors can impede and limit reach. The offshore industry presents research that displays the influence of external factors that impact reach capability. Personal protective equipment, life-suits and vests create barriers on reach, that impede reach capability in helicopters and life boats (Kozey et al. 2009, Reilly et al. 2005). These findings proved vital in the placement of levers such as door latches for safety of offshore workers. Similarly, research completed by Chaffin and colleagues, investigated factors impeding reach during driving. It was determined that there can be external factors (seatbelt) and internal factors (posture) that impact driver reach (Chaffin et al. 2000).

Age, an intrinsic factor that contributes to biomechanical and physiological changes may impact the reach envelope. Degenerative diseases such as arthritis decrease mobility and strength in older samples (Omoumi et al., 2011). Molenbroek (1998) used similar tracing methodologies on whiteboards as outlined by Maynard (1934) to observe the reach envelope of older adults. Although this method was not fully dynamic nor did it capture volumetric reach, it presented shorter reach distances for older adults in comparison to young adults (Molenbroek, 1998). Gender was also found to be a significant factor on the reach envelope (Faulkner & Day, 1970). A female reach envelope was on average 13.5 % smaller than the maximum male reach envelope

(Sengputa & Das, 2000). The 5th, 50th and 95th percentile reach envelopes generated from the work of Sengupta and Das (2000) were the first functional reach data sets available for both seated and standing industrial workspaces.

Other intrinsic factors of a person's ability to reach may be resultant from inferior anatomy of the body and not just the upper extremity. For example, Kozey and Das (2004) investigated reach envelopes for adult wheelchair users with spinal cord injury for accommodation design in the industrial workspace. The maximum reach envelopes of the adult wheelchair users were significantly smaller than an asymptomatic cohort (Kozey & Das, 2004). The maximum reach envelopes only were 58.2%, 78.8% and 94% of the recorded 5th, 50th and 95th percentiles of an asymptomatic adult sample recorded by Sengupta and Das in 2000 (Kozey & Das, 2004). This highlighted that intrinsic factors (injury, degenerative diseases of the joints) as well as extrinsic (wheelchair or equipment) can both impact the reach envelope of a person. The factors that affect reach are still emerging which highlights the relevance of the reach envelope as a useful measurement.

2.4 Measuring the effect of load on MRE

As there is no set standard in completing upper extremity movement analysis, the method of quantifying the reach envelope is still developing. While many variations have been previously described, the reach envelope should reflect functional dynamic movement. In tasks one performs, functional dynamic movement often includes maneuvering objects through reaching (Ayoub, 1989). Many occupations and reaching tasks in daily life involve maneuvering small loads in a given workspace. For example, working at a checkout stand would require an operator to lift small items such as a can of soup within the reach envelope. An activity of daily life that encompasses reaching and loads could be placing that same can of soup up and onto a shelf in the kitchen cupboard.

The addition of loads does significantly impact the shoulder joint (Das & Wang, 2004). Shoulder moments (torques) increase as the load and moment arm increase in order to complete necessary reaching motions. Das and Wang (2004) recognized the requirement of strength in understanding the reach envelope. They measured the strength ability of an individual pushing and pulling at specific reach heights and angles within the reach envelope. The largest pulling strength capability was directly vertical above the shoulder for all participants (Das & Wang, 2004). Pulling was also favoured over pushing as the push strength was only 71% of that of pulling (Das & Wang, 2004). Angular position of the joints such as amount of elbow flexion and extension played a role in these motions (Das & Wang, 2004). The strength required to push and pull objects within the reach envelope could influence the overall dimension of the reach envelope and these authors were one of few to document this. Sengputa and Das (2004) studied the reach envelope and its resulting cost on physiological variables of oxygen consumption, heart rate and electromyographic activity of a repetitive work task. The tasks performed in the normal reach envelope in comparison to the maximum reach envelope had an increase in oxygen consumption and heart rate by 19%, and 6% respectively (Sengputa & Das, 2004). The average activity of the anterior deltoid, upper trapezius and erector spinae increased as well (Sengputa & Das, 2004). The findings indicated that tasks performed in larger envelopes are associated with an increase in physiological cost (Sengputa & Das, 2004).

Dynamic functional movement of small loads in completing reaching motions may not just require pushing or pulling in single planes of motions as measured by Das and Wang (2004). Instead movement of small loads or objects often span across the entirety of the reach envelope. One of the first studies to look at the effect of small external loads while measuring reach envelopes was completed using 0.0 Kg, 0.5 Kg, and

1.0 Kg loads (Johnston, et al., 2016). This study used the previously described CPSAM three dimensional motion capture device and incorporated the aforementioned loads while recording reaching trials. By adding a small load into the subject's grip during reach recordings, there was preservation of the dynamic nature of reach while adding an additional factor. The addition of small loads of 0.5 or 1.0 Kg decreased the total reach envelope volume by approximately 6 % for a young adult sample (Johnston, et al., 2016).

2.5 The Complexity of the Upper Extremity

The anatomy of the upper limb makes it a complex system to measure with kinematics. At the glenohumeral joint, the interaction of the humeral head and the glenoid cavity is reliant on muscular and ligamentous stabilization. The labrum (articular cartilage) located in the ball and socket joint between the humeral head and glenoid decreases frictional properties between the two bones. The rotator cuff is comprised of four muscles, supraspinatus, infraspinatus, teres minor and subscapularis. These muscles stabilize the shoulder through supporting the position of the humeral head into the socket of the glenoid. They are prime movers in many rotational motions of the upper extremity. Other joints also cross and interact with the shoulder, especially in performing reaching motions. Three of importance to reach include the sternoclavicular and acromioclavicular joints, and the scapulothoracic joint. Figure 2 displays the bony structure of the shoulder joint.

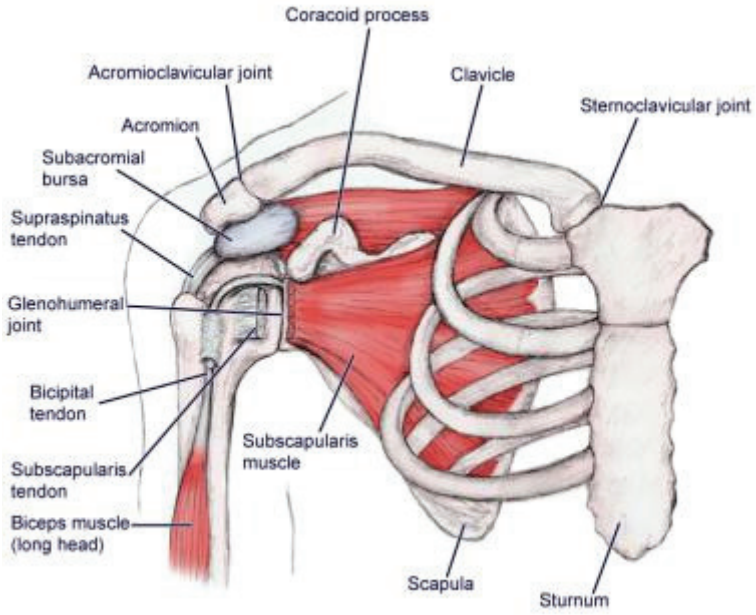


Figure 2 Anatomy of the Shoulder, anterior view. Retrieved from http://emedicine.medscape.com

With the variety of anatomical structures and tissues surrounding and contributing to the shoulder joint it can be difficult to truly pinpoint glenohumeral movement. An often overlooked in modeling reach is the motion of the scapula. Methods often focus on measuring reach from a fixed location such as the acromion (Sengupta & Das, 2000), yet mobility of the scapula greatly contributes to reach movements. The scapula has translational, protraction, and retraction capabilities that will influence to overall reach distance. These movements of the scapula are difficult to track in motion analysis due to the surrounding musculature and the posterior position relative to the shoulder. In modeling the shoulder joint, Abdel-Malek and colleauges (2004) addressed the shoulder joint with multiple degrees of freedom (DF) both translational and rotational. However, reach envelope collection measures assume a 3 DF model due to the static capture of the acromion position. Where the shoulder performs flexion/extension, abduction/adduction and rotation.

The elbow joint is another primary joint contributing to reach motions. Typically, the elbow is ignored in a MRE measurement as it assumes a fully extended elbow joint with no movement. The normal reach better depicts the contribution of elbow movement in the horizontal working plane (Maynard, 1934). As a modeled hinge joint, the elbow primarily completes flexion and extension motions, however, it has small amounts of rotational ability as well (Yang et al. 2004). Typically, the elbow is modeled with 1 degree of freedom in upper limb movements (Abdel-Malek et al., 2004).

Finally, the most distal joint is the wrist, an extremely mobile joint with condyloid articulation (Abdel-Malek et al., 2004). In a complex model this joint has been given up to three degrees of freedom to present the spherical motion of the revolute joint (Yang, Abdel-Malek, & Nebel, 2003). For the purpose of reach envelope measurements,

and understanding the workspace of the upper limb the wrist is not included in MRE models. Abdel and colleagues (2004) stressed the importance of understanding the workspace not only for ergonomic posture but for understanding joint motion and neural strategies for successful reaching task movements. These authors described the reach envelope as a function of the spherical shoulder joint and the revolute elbow joint (Abdel-Malek et al., 2004).

Focusing primarily on the shoulder and elbow as primary movers for reach is a simplification of the biomechanical and anatomical capabilities of the upper extremity. Trunk motion, scapular, thoracic, and clavicular movement, and wrist motion do contribute to reach yet are more difficult to model in dynamic movement (Abdel-Malek et al., 2004). With the understanding that the upper limb anatomy is complex with varying degrees of freedom it is well supported that reach cannot be entirely proportional to arm length throughout a dynamic reach envelope (Das & Behara, 1998; Kennedy, 1978).

2.5.1 Rotator Cuff Injuries

Rotator cuff injuries have a high prevalence in the Atlantic Region and nationally. Subsequent to the lower back, the shoulder is the second most affected area from workplace injuries in Nova Scotia (WCB Nova Scotia, 2012). Rotator cuff tears are one of the more common injuries about the shoulder joint (Nho et al. 2008). Mechanisms of RCTs include degenerative tears (from repetitive overuse, often seen in older patients), acute tears (trauma, or dislocations in those over 40 years) and iatrogenic tears (post operatively following shoulder surgery) (Jaeger, 2014). Knowledge regarding the etiology underlying RCTs, appropriate tests for diagnoses, treatment recommendations have continued to improve in recent years. The etiology of RCT can be broken down into

intrinsic and extrinsic factors (Neviaser, Andarawis-Puri & Flatow, 2012). Extrinsic factors include trauma out outsourced injury resulting in shoulder instability. Intrinsic factors include age (increasing age is positively correlated with an increased prevalence of degenerative tears tendon metabolism, genetic factors and vascularisation (Cheung, Silverio & Sperling, 2010). The structural anatomy of the shoulder joint is a large factor in the instability of the joint. Rotator cuff tears are classified into two groups: partial and complete tears. A partial tear is when the tendon is torn but remains intact between two structures. A full or complete tear is when the tendon becomes completed detached from the bony structure and can be greater than 3.0 cm in depth.

Since RCTs are common there is a need for research regarding not only the prevention but treatment of the tears. Surgical intervention is under constant improvement and can benefit from a robust measure of functional capability of the shoulder. The maximum reach envelope presents a tool that has not yet been paired to clinical applications. Further measurement and assessment methods may benefit from greater understanding of three dimensional movements.

2.6 Summary of the literature

The ergonomics literature primarily focuses on the MRE measurement on asymptomatic populations. The productive design of the workspace requires quantification of reach and an understanding of the factors that can facilitate or impede the gross measurement (Kennedy, 1978) (Sengputa & Das, 2000) (Kozey & Das, 2004). Design research presented reach envelopes as a reference dimension measure to a variety of workspaces (Abdel-Malek et al., 2004; Das & Wang, 2004). The literature has also identified a handful of key factors of that can affect the MRE measure. Research has primarily focused on able groups, with little to no documentation of physical impairment.

There are still some limitations that need to be addressed within measuring reach in asymptomatic individuals. However, measurement of three dimensional reach has come a long way and is feasible to collect. While it may be difficult to understand the application of reach measures to symptomatic and injured individuals, the current literature is reassuring that there are potential novel applications of the MRE measure in clinical domains of measurement. With the prevalent concern of rotator cuff tears and shoulder injuries, current literature favours potential clinical applications of reach measures.

CHAPTER 3 METHODOLOGY

A pilot study conducted by Johnston et al. 2016 developed the appropriate methodology for the collection of the MRE used in this study. The current methodology adapted the previous methods created by Sengupta and Das (2001), and Kozey and Das (2004) in which a computerized potentiometric system was used to collect three-dimensional motion capture of the maximum reach envelope. The effects of load, age, and injury on the reach envelope were investigated using the following protocol. A quasi-experimental design approach addressed group factors such as symptomatic shoulder injury on maximum reach envelopes. The following chapter outlines the study sample, measurement tools, protocol, and data processing procedures.

3.1 Study Samples

Three participant groups were recruited for this study. Group 1 was a symptomatic (full massive rotator cuff tear shoulder surgery candidate) group, Group 2 was an age-similar group of asymptomatic controls, and Group 3 was a secondary analysis of a previously collected young adult, asymptomatic group (Johnston et al., 2016). Using data from a local Orthopaedic clinic, the age demographics for the symptomatic group were determined, and further used to calculate a stratum for the age-similar control group. Data collected from a previous reach envelope investigation (Johnston et al., 2016), provided the necessary sample size calculation. It was anticipated that the expected difference in MRE due to participant group would be larger than the observed differences in MRE due to load. In order to achieve a similar power as the previous study (power of at least 0.8), a power calculation required at least 28 participants total. Therefore, recruitment aim was to have 10 participants in each of the participant groups. For this study 20 participants were completed using primary data

collection, and 10 participants' data was collected through secondary data analysis (Johnston et al., 2016). The convenience sampling method formed three anticipated study groups containing 10 participants per group.

A review of the age and gender of 64 patients previously seen by Dr. Wong in his orthopaedic clinic produced the following demographic data: mean age ($\pm$SD) was 59 ($\pm$9.4) years with no significant difference in age between men and women, 30% of the sample were women (age 59$\pm$ 8.3) and 70% of the sample were men (age 58 $\pm$ 9.8). Using these data, a profile of the requirements for a stratified random sample with 10 age similar, asymptomatic was developed. Three strata based on age were determined: Strata 1 $\leq$ 49 years (Mean-1SD), Strata 2 between 50 and 69 years (Mean$\pm$ 1 SD), and Strata 3 > 69 (Mean+1SD) with proportionate representation of 17%, 66% and 17%, respectively. This produced 2, 6 and 2 participants per strata within each group with a slight over representation in the two smaller strata. There was an over-sampling of female participants to maintain a minimum of 40 % representation easing strata group development (4 per group, 1-2-1 in each strata).

The symptomatic participants were recruited and signed informed consent with the research assistants at the Orthopaedic Clinic at the Halifax Infirmary Hospital. Dr. Wong's Orthopaedic Clinic completed the clinical assessments and diagnoses of the symptomatic participants. An eligible symptomatic participant was deemed to have a full thickness massive rotator cuff tear. The asymptomatic participants were recruited from the Halifax Regional Municipality with posters and personal communication within the Dalhousie University community.

Groups 1 Symptomatic shoulders

The eligible symptomatic participants were identified by the orthopaedic surgeon to have a full thickness rotator cuff tear which was defined as a complete detachment of any rotator cuff muscle (subscapularis, infraspinatus, supraspinatus or teres minor) tendon from the head of the humerus. The full thickness tear greater than 3.0 cm was measured using magnetic resonance imaging and diagnosed by the orthopaedic surgeon. Participants were invited to participate regardless of shoulder function, or perceived capability of completing the study. If they were comfortable to try the study and consented to the requirements they were included.

Groups 2 and 3 Asymptomatic shoulders

Group 2 (age-similar asymptomatic) inclusion criteria was based upon age, gender, and previous report of shoulder injury. Convenience sampling targeted the age, and gender criteria, and these individuals were eligible if they had no previous self-report of a shoulder injury (Appendix F). Similarly, the previously collected data of Group 3 (young adult asymptomatic) was based on the inclusion criteria of greater than 18 years old, where no subjects were greater than 30 years of age.

Due to recruitment issues and timeframe, only 26 participants were used in this study. Both asymptomatic groups met the initial aim of 10 participants, but the symptomatic group only had 6 participants. Researchers within the Occupational Ergonomics and Biomechanics Lab at Dalhousie University completed reach, and clinical measurements, however, all symptomatic diagnoses were made by the surgeon. Participants had the option to remove themselves from the study at any point during data collection, or within 2 weeks of completing their reach trials.

3.2 Structural and Functional Measures

The measured structural and anthropometric measures included height, weight, seated height, seated acromial height, upper arm and fore-arm hand lengths as created by the anthropometric requirements for the design of workstations (International Organization for Standards, 2013). The anthropometric measures and required landmarks are outlined in Table 1. Length and vertical measurements were completed using a measuring tape and recorded to the nearest millimeter. Weight was measured in kilograms on a balance scale and measured to the nearest 0.1 Kg. Shoulder range of motion (ROM) was assessed both in clinic for Group 1 participants (clinic routine) and during reach data collection for all participants. A goniometer was used to measure ROM including flexion, extension, abduction, adduction, internal, and external rotation of the shoulder following the Nova Scotia Health Authority Orthopaedic Assessment Guidelines (Appendix C). Strength measurements were completed using a hand-held dynamometer (*MicrofetII*, Hoggan Scientific 2015) at both locations for Group 1, and post reach envelope collection data collection for all groups. ROM, strength collection protocols were taught by the orthopaedic clinic to the researchers prior to commencement of the study. These protocols, and the data collection form are attached in Appendix B. All structural, strength and range of motion measures were completed by one member of the research team to improve inter-rater reliability and decrease human error.

Table 1 Anthropometric Measures

Measure	Code	Description
Stature	STAT	Subject stood unshod in the anatomical position. The measurement was made from the vertical distance from the floor to the top of the head. (mm)
Weight	W	Standard measure on balance scale (Kg)
Seated Height	SITH	Subject sat in collection chair with head oriented forward as in the anatomical position and feet resting on the platform surface, chair adjusted so the knees are bent at approximate right angles. The vertical distance from the floor to the top of the head was measured. (mm)
Seated Acromial Height	SITAH	Similar to the seated height protocol, the vertical distance from the floor to the right acromion was measured. (mm)
Seated Elbow Height	SETAH	Similar to previous, the vertical distance from the floor to the right elbow was measured. (mm)
Upper arm length	UPARL	Subject stood with right arm extended at side in the anatomical position. The distance along the dorsal vertical axis of the arm from the tip of the 2nd phalange to the acromion was measured. (mm)

3.3 Data Collection

A computerized potentiometric system for structural and anthropometric measures (CPSAM) was used to record the maximum reach envelope (Das, Kozey & Tyson 1994). The electromechanical system was inserted into a signal conditioner then connected analog to digital convertor. Figure 3 displays the brief process flow from the initial collected voltages of each PRU to the output of coordinate data. Voltage data was produced by the movement of four potentiometers (10 turn voltage change) attached to 4 respective pulleys, hereinafter PRU.

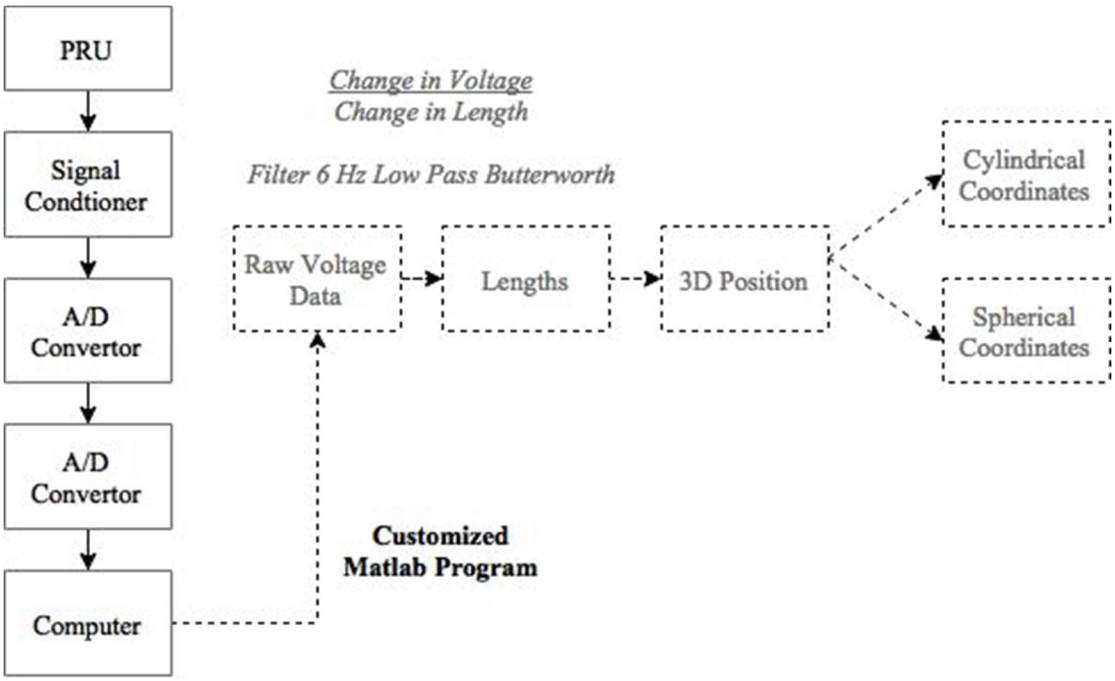


Figure 3 CPSAM organizational set-up

CPSAM was a wall mounted system consisting of four primary recording potentiometer units (PRUS) with four strings that attached to a common stylus. This electromechanical system used the movement of a hand-held stylus to track and record three dimensional kinematics of a single point in space. Since its foundation in 1994, the system has undergone extensive testing to minimize sources of errors in detecting a position in three dimensional space. Such testing included small reports on the tensile properties of the strings, string deformation, signal conditioners, and calibration with a gold standard Certus system. With an average measured error of +/- 5.0 mm in comparison to a Certus 3D motion capture system, it was accepted that this system would produce gross reach envelope data appropriate for this application.

3.4 Protocol

Data collection protocol used in the laboratory is depicted in Figure 4. The data collection period took approximately one hour consisting of consent, anthropometric and functional measures, and CPSAM reach envelope collection. Participants recruited with a rotator cuff tear were consented by the research assistants of the orthopaedic clinic and then forwarded to the researchers at the Dalplex. A period of information, questions and concerns was provided for each participant upon entering the lab. Consent forms were stored in a locked filing cabinet apart from data to respect subject anonymity. Basic anthropometrics and functional measures outlined in Section 3.2 (ie. Height, weight, strength, ROM) were measured by a team of two researchers and entered onto the appended data collection form (Appendix F).

Reach movement collection using CPSAM was completed after the anthropometric and ROM measures. The data collection area consisted of a platform with a chair in the center of it. CPSAM and the 4 PRUS were mounted directly in front of the platform area on the wall (Figure 6). The chair was rotated between two orientations; front and side facing, which were collated to produce the total reach envelope volume (Figure 4). Asymptomatic participants completed 12 reach trials in total which took approximately 30 minutes depending on the participant. Some symptomatic participants took the same approximate number of trials and time, whereas others were given longer rests, and the length of a trial (45 seconds) was decreased to 3 15second collections to minimize occurrence of discomfort. Figure 4 displays the organization of a data collection, along with the instructions of any given reach trial. Where this study was only interested in measuring MRE kinematics other dependent variables such as time to complete were not standardized. In working with a clinical population, it was imperative

that collection be more tailored to their capability without losing the three dimensional kinematic measures.

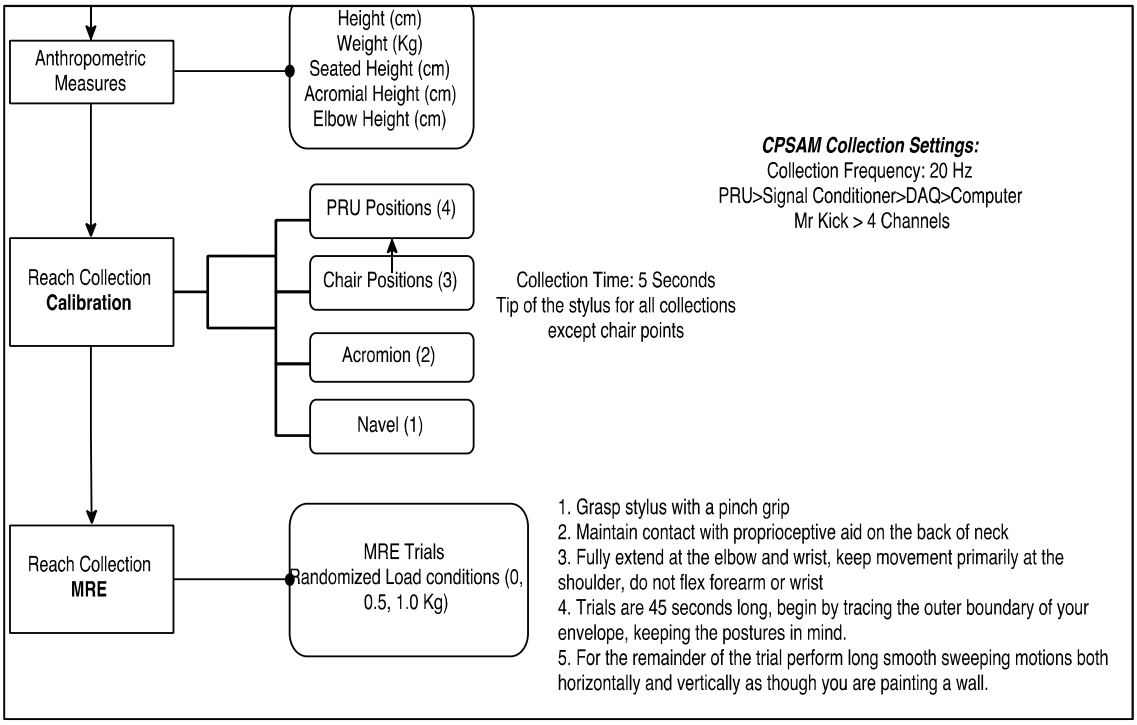


Figure 4 Reach collection protocol at Dalhousie University

3.4.1 Using CPSAM to collect Reach Envelopes

The initial positions of both the chair and the subject were required prior to reach collection trials. These positions provided the coordinates needed to orient the participant in space and created a rotation matrix that was used in the latter phase of data analysis to combine front and side facing data sets. Using a custom platform, three positions of the chair were recorded by placing the base of the stylus on standardized marked areas. The initial orientation was randomized between front and side facing (Figure 5). The participant was first seated in the chair and four anatomical landmarks (acromion, olecranon process, inferior and superior notch of the sternum) were recorded by placing the point of the stylus at each bony landmark location. Participants completed the 6 reach

trials in the first randomized orientation with the small loads of 0.0 Kg, 0.5 Kg, and 1.0 Kg randomized throughout. Participants always began with a familiarization trial, followed by the 0.0 Kg condition first. The chair was then rotated 90 degrees counter clockwise if the first set was completed front facing, or 90 degrees clockwise if a participant completed side reaching trials first. The standardized calibration points on the chair, and the bony landmarks were recorded a second time in the subsequent orientation. The remaining 6 reach trials were completed in the subsequent orientation, again beginning with a 0.0 Kg load trial followed by randomization of the remaining loads.

Figure 5 CPSAM with front(left) and side (right) facing orientations. Highlighted in the upper right corner is a close-up of a primary recording unit (PRU)

A reach trial consisted of a participant "painting" their maximum reach envelope. Grasping the stylus in a comfortable pinch grip (base of the stylus held between the thumb and phalanges), they were instructed to first trace the outer boundary of the largest volume they could reach. Feedback to the participant was given to remind them to keep an upright seated position with minimal trunk movement, and a straight arm with no movement at the elbow or wrist joints. A padded contact located behind the head of the participant was used as a proprioceptive aid for tactile feedback on subject's trunk posture. The researcher made subjective observation to ensure head contact with the pad and elbow extension maintained throughout reach trials. From this trace, participants were instructed to move the stylus through the remainder of the space they had generated. Participants were instructed to use horizontal and vertical sweeping motions to fill in the remainder of the trace. Participants had 45 seconds to complete a trial and fill in the space. This time was adjusted to 15 second trials if the participant deemed the 45 second trials as too fatiguing.

3.5 Conditions

A loaded maximum reach envelope was used in one pilot study completed by this research team (Johnston et al., 2016). The three load conditions were incorporated based upon the previous study: 0.0 Kg, 0.5 Kg and 1.0 Kg. These plate weights simulate the typical weight ranges of a wrench or handheld tool in an industrial setting, however, they are similar weights to that of many activities of daily living (Ayoub, 2014). The load conditions were discussed with the research team and orthopaedic surgeon prior to commencing the study. It was anticipated that these weights would not put the

symptomatic individuals or any asymptomatic individual at further risk of injury. Load was introduced only at the second trial after a familiarization trial and the initial 0.0 Kg reach trial. Participants completed 2 reach trials for each of the 3 load conditions.

The symptomatic sample may have different movement patterns within the reach envelope. As a result, full extension of the arm may not be possible throughout the entire reach volume. The researchers understand this limitation, however, we will instruct participants to attempt full extension as best as possible but perform the necessary arm movements to cover the largest volume of space during reach trials. Notes will be made if the subject performed elbow/wrist flexion extension in order to complete the trial.

3.6 Data Analysis

3.6.1 Data Processing

The voltages from the PRUS (4 units) were collected using a customized software interface (Labview 2012). Data was sampled at 20Hz, for 45 or 15 seconds of each reach trial. The data is passed through an analog to digital converter (National Instruments DAQ BNC-2110) using LabVIEW© data collection software. The raw voltage data was passed through a 2nd order Butterworth low pass filter set at 6 Hz (Winter, 2005). Customized Matlab® software computed the relationship between the voltage change of the four potentiometers and the length of the four strings during standardized calibration procedures to determine a conversion of volt to length change. The voltage to length change

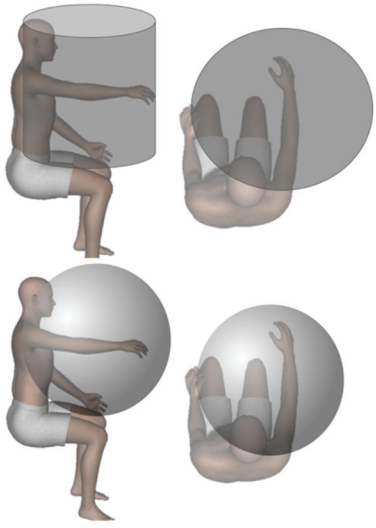


Figure 6 Modeling the reach envelope (cylindrical top) and (spherical bottom)

coefficients were calculated using a 2nd polynomial equation unique to each PRU. The general form of the equation is shown in equation 1.

$$Length = \beta 0 + \beta 1\, x\, Voltage + \beta 2\, x\, Voltage2 \qquad \text{[Eq'n 1]}$$

The positions of the 4 PRUs in space were previously determined using the Certus Optotrack 3D camera system. The positions and the length (L_i) from each PRU to the common stylus point determines the coordinates of the stylus using a least squares optimization equation to minimize the associated error. Where, x_i, y_i, and z_i is the unknown point on the stylus, $L_{1,2,3,4}$ are the known lengths and $X_{1,2,3,4}$ $Y_{1,2,3,4}$, $Z_{1,2,3,4}$ are the known positions of the PRU in space:

$$\begin{aligned} Err = \quad & [(L^2_1 - ((x_i\text{-}x_1)^2 + (y_i\text{-}y_1)^2 + (z_i\text{-}z_1)^2) \\ & + (L^2_2 - ((x_i\text{-}x_2)^2 + (y_i\text{-}y_2)^2 + (z_i\text{-}z_2)^2) \\ & + (L^2_3 - ((x_i\text{-}x_3)^2 + (y_i\text{-}y_3)^2 + (z_i\text{-}z_3)^2) \\ & + (L^2_4 - ((x_i\text{-}x_4)^2 + (y_i\text{-}y_4)^2 + (z_i\text{-}z_4)^2)] \end{aligned} \qquad \text{[Eq'n 2]}$$

The two trials of each load condition across both orientations were combined to produce one total maximum reach envelope for each participant. The front and side facing orientations were merged using a calculated rotation matrix from the chair and anatomical landmark positions collected in the calibration phases of data collection. The final output was a point cloud of approximately 3600 data points over the entire merged envelope. This final output was calculated as 3D Cartesian coordinates *(x, y, z)* relative to the acromion.

3.6.2 Cylindrical and Spherical Modeling

In order to model the reach envelope, reach vectors were calculated using the Cartesian coordinates previously calculated in Matlab. The reach vectors were calculated as the distanced between the measured acromial position and position in space in two coordinate systems. The models were created by both a cylindrical (R_{cyl},θ,Z) and spherical (R_{sph},θ,ϕ) coordinate system. Figure7 displays a visual representation of the reach envelope as a cylinder and sphere with respect to the participant. These two methods of modeling the reach envelope emerged with previous work in reach envelope quantification. In the pilot analysis of 10 asymptomatic participants, both methods were applied. Appendix B displays a brief overview of the conversion from 3D Cartesian coordinates to both of cylindrical and spherical coordinates. The converted systems still produced 3600 data points representing the MRE. These systems were then reduced by paneling the data into cutoff grids about the acromion.

In reference to the top image in Figure 8, for any given cylindrical coordinate system:

- the transverse plane of MRE was sectioned into 9 angular bands of 30 degree increments bands about the acromion (theta bands);
- the sagittal plane of the MRE was sectioned into 6 horizontal bands of 200 mm above or below the acromion (height or Z bands);
- a given cylindrical MRE was reduced to 54 panels in total combining the bands.

In reference to bottom Figure 8, for any given spherical coordinate system:

- the transverse plane of MRE was sectioned into 9 angular bands of 30 degree increments bands about the acromion (theta bands);
- the sagittal plane of the MRE was sectioned into 8 angular bands of 30 degree increments about the acromion (phi bands);
- a given spherical MRE was reduced to 72 panels in total combining the bands.

Within each panel the associated reach vector $R_{cyl\ or\ sph}$ was determined as the mean, standard deviation, and median values of all data points collected in that panel.

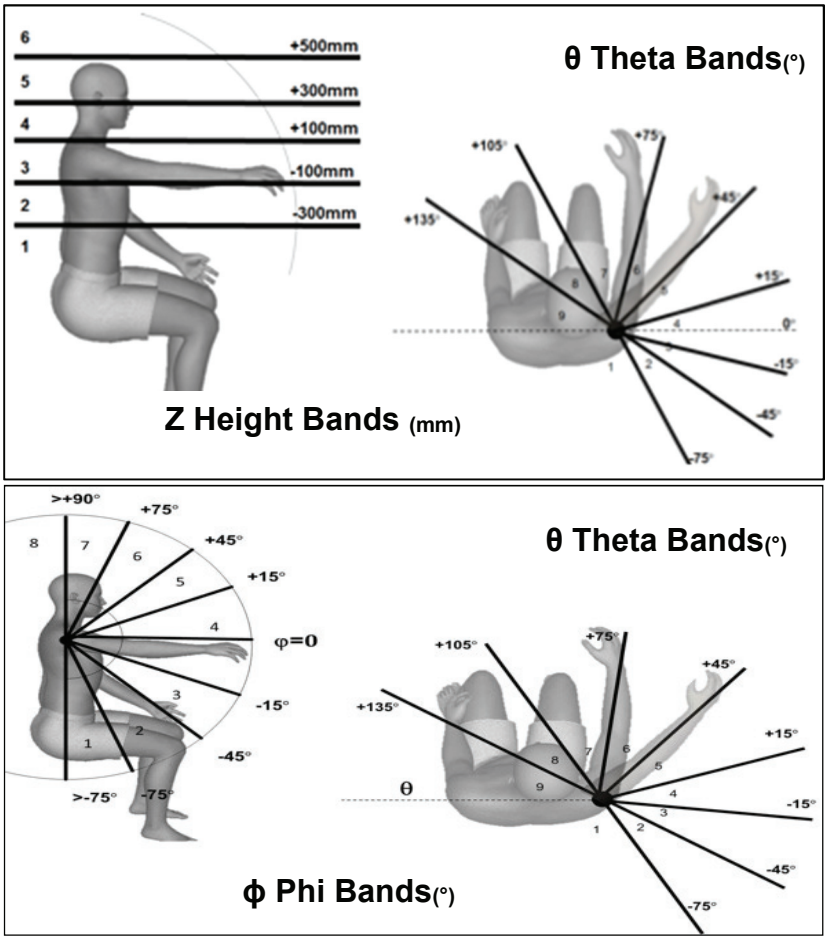


Figure 7 Top - Cylindrical paneling of the MRE, Bottom - Spherical paneling of the MRE

3.6.3 Analysis

In order to complete this research, and achieve target goals, multiple analyses were required. No one set analysis provided the best answer to the stated objectives; instead a combination of analyses returned useful information. Analyses needed to take into account a) distance of reach, b) area of reach, c) factors affecting either or both of the previously mentioned measures.

Comparison on cylindrical and spherical coordinate systems was a first step in the analysis. While both methods have been used in previous research, there are strengths and limitations to each. In previous work, the cylindrical model sectioned the reach envelope into horizontal planes of absolute cut off values in Z level below or above the acromion level. The absolute cutoffs created reach envelopes that had later effects on the interpretation of reach for shorter stature, or arm length individuals. This problem was addressed with the spherical method. Gridded colored maps were be produced for both cylindrical and spherical methods to present the frequency of participants reaching into a panel. The colour bar could be set to indicate number of participants or portion of arm length, depending on if the analysis was group or individualized comparison. These maps displayed paneled sections of data as outlined by the cut off values of the varying Z, ϕ, and θ sections. As a comparative analysis, the frequency maps will identify areas within the two coordinate modeling systems that may impact further interpretation. The maximum reach envelope measurement results may have implications in both workspace design and rehabilitation.

The main independent factors of this investigation were: subject sample group (3) – young asymptomatic, older asymptomatic, symptomatic shoulder; load condition (3) – 0, 0.5, 1.0 Kg; and the division panels of the spherical coordinate system (72 panels in total for this coordinate system). The dependent measured variable was the reach distance vector from the acromion to the reach position in space or the normalized equivalent. Once the data was divided into the paneled regions of the reach envelope, analyses were dependent on statistical assumptions, overall objectives, and target audiences. Due to the levels of independent variables typical parametric analysis such as Analysis of Variance (ANOVA) posed limitations, however a general linear model (GLM). The GLM was completed in a variety of ways, due to resulting fits and model parameters. The included variables are outline in the respective results sections. Other explored analyses included principal component analysis (PCA) and logistic regression.

CHAPTER 4 RESULTS

In order to address the initial objectives of this research study multiple analyses and results were completed. Given the sample sizes and the various types of data (interval-ratio and categorical) both parametric and non-parametric analyses were performed. This chapter is sectioned based on the initial objectives, along with the target results and target audiences of the application of this research. The analysis and interpretation of the collected data addressed the following objectives:

a) Compared the use of cylindrical and spherical coordinate systems in describing and quantifying the MRE.

b) Investigated the effectiveness of multivariate analyses in determining differences in the MRE;

   a. Proof in principle analyses of principal components and logistic regression.

c) Compared the effect of small hand held loads on the maximum reach envelope of 3 subject groups: young asymptomatic, age-matched asymptomatic, and symptomatic (rotator-cuff tear);

   a. Compare reach distance (R continuous variable),

   b. Compare reach area (Reached 0 or 1 categorical variable).

4.1 Descriptive statistics

The data was composed of 3 participant groups nominally described as: young asymptomatic, age-matched asymptomatic, and symptomatic (rotator-cuff tear). Initial recruitment included 10 age-matched, and 10 symptomatic participants, however, only 6 symptomatic participants were measured due to recruitment delays. The age-matched asymptomatic were recruited through the staff at Dalhousie University, and word of mouth communication in the Halifax Regional Municipality. The age matching was based on the previously described stratum in Chapter 3 provided by a sample of 60 surgical candidates not the subset recruited for this thesis. Tables 2, 3, and 4 display the descriptive statistics, anthropometric measures, and clinical range of motion, strength measures of the participants. It is noted that the younger asymptomatic group was a secondary analysis of previously collected data (Johnston et al., 2016), therefore it includes a subset of the aforementioned measurements.

Arm length, a key variable in determining absolute reach distance had mean values of 69.8, 74.9 and 71.7 cm for the symptomatic, age-matched asymptomatic and young asymptomatic groups respectively. These were compared using a univariate one way ANOVA, there were no significant differences were found across the groups ($F_{(2,24)}$=2.07, p=.148). Using independent t-tests across the range of motion (ROM) measures, only 3 measures were statistically different between age-matched and symptomatic groups. The ROM data was only available for the age matched group and the symptomatic group. Six of the measures were interval-ratio measures and therefore these were compared using independent t-tests. Two measures (active external and internal rotation) were taken using the score system from the Clinical Measures Sheet in Appendix F. These values were coded as ordinal numbers ranked 1-5) are presented as

the mode along with the mean (SD) of the continuous ROM data in Table 3. Only 3 range of motion measures were statistically different between age-matched and symptomatic groups. There were significant differences between group means of active and passive abduction ($t_{(15)}=3.43$, $p<.05$; $t_{(15)}=2.80$, $p<.05$) and passive external rotation ($t_{(15)}=2.91$, $p<.05$). Average strength was significantly different between the symptomatic and age-matched asymptomatic participants. For all strength measures the mean strength recordings for the asymptomatic group was greater than the symptomatic group (abduction $t_{(15)}=6.10$, $p<.001$; external rotation $t_{(15)}=6.51$, $p<.001$; internal rotation $t_{(15)}=3.27$, $p<.001$).

Table 2 Descriptive statistics of participants by group N=26

Note: Young Asymptomatic group was a secondary analysis, * represents uncollected data.

		Age	Height	Weight	Seated Height	Seated Acromial	Seated Elbow	Arm Length
Symptomatic	Mean	61	165.1	76.7	129.5	101.4	70.0	69.8
3 Male 3 Female	*SD*	*8*	*11.9*	*19.8*	*5.8*	*7.7*	*6.2*	*5.3*
Age-Matched Asymptomatic	Mean	52	175.4	75.3	139.2	101.2	63.1	74.9
6 Male 4 Female	*SD*	*13*	*10.0*	*7.8*	*16.9*	*5.4*	*15.8*	*5.6*
Young Asymptomatic	Mean	22	173.5	81.9	*	103	*	71.7
5 Male 5 Female	*SD*	*2*	*5.4*	*16.9*	*	*2.1*	*	*2.9*

Table 3 Range of motion ROM measures by group

Note: Mean +/- SD Young Asymptomatic group was a secondary analysis, this data was not collected. Active internal and external rotation: Mode

		Active				Passive			
		Flex	Abduct	Ext Rot.	Int Rot.	Flex	Abduct	Ext Rot.	Int Rot.
Symptomatic	Mean	133	**105***	4	3	153	**131***	**59***	49
	SD	47	44			37	29	12	16
Age-Matched Asymptomatic	Mean	173	**169***	5	4	177	**166***	**80***	54
	SD	8	18			5	12	15	17

Table 4 Strength measures by group

Note: Young Asymptomatic group was a secondary analysis; this data was not collected. (lbs of force)

		Abduction*	External Rotation*	Internal Rotation*
Symptomatic	Mean	10.3	6.8	13.3
	SD	*5.7*	*2.6*	*10.1*
Age-Matched Asymptomatic	Mean	31.0	24.2	28.3
	SD	*7.1*	*6.2*	*8.4*

4.2 Reach envelope data format

The methodology in calculating reach distances was presented in Section 3.6 of the methods. The maximum reach envelope (MRE) was panelled into 72 panels of the spherical coordinate system. The median reach distance vector of each of these panels was calculated for each participant, and then normalized for each person as a proportion of arm length. Shown in Tables 5 – 7 are overall mean and standard deviations for the panels. The same values normalized by arm length are displayed in Tables 8 – 10 for each of the 3 groups. Reading the tables from left to right displays the theta regions dividing the transverse plane about the vertical axis of the acromion (behind right side moving across the body to the left side). Reading the vertical direction of the tables top to bottom displays the angular regions dividing the sagittal plane about a mediolateral axis of the acromion, below acromial level (-) to above acromial level (+).

No participants from any of the groups reached into the highest region of phi greater than 90 degrees. Visually, the symptomatic group had smaller absolute reach distances across the MRE compared to the asymptomatic groups. Since the previous ANOVA detected no difference between arm lengths of the 3 groups the differences in the groups was not attributed to arm length. The normalized data was an attempt to decrease the known influence that arm length had on the chance of finding significant differences in MRE comparisons (Chaffin et al., 2000). The normalization created a measure that could be compared across all groups. The normalizing processed involved the anthropometric measure of arm length using the following equation:

$$proportion\ R_{norm} = \frac{R_{absolute}(mm)}{Arm\ length\ (mm)} \qquad \text{[Eq'n 3]}$$

4.2.1 Tables of absolute reach distance

Table 5 Average median reach distance in each panel Mean (SD): Group Young Asymptomatic (n=10)

Phi Band (degrees) \ Theta Band (degrees)	< -75		-75 : -45		-45 : -15		-15 : 15		15: 45		45: 75		75 : 105		105: 135		> 135	
< -75			803	(99)	712	(16)	742	(94)	785									
-75 :-45	711	(58)	677	(40)	655	(35)	652	(45)	674	(75)	689	(82)	701	(60)	719	(71)		
-45:-15	740	(26)	657	(45)	619	(38)	602	(41)	616	(52)	660	(63)	681	(63)	725	(75)	757	(82)
-15: 15	667	(131)	644	(52)	599	(49)	577	(52)	585	(56)	628	(60)	663	(66)	712	(73)	749	(80)
15 :45	742		658	(59)	612	(59)	587	(59)	589	(65)	616	(66)	654	(67)	702	(73)	743	(73)
45 : 75	534	(2)	661	(95)	639	(69)	624	(67)	624	(66)	625	(75)	654	(69)	688	(73)	714	(66)
75 : 90	652	(74)	663	(63)	658	(51)	631	(81)	630	(86)	630	(80)	643	(67)	646	(83)	644	(99)
> 90																		

Table 6 Average median reach distance in each panel Mean (SD) Group: Age-Matched Asymptomatic (n=10)

Phi Band (degrees) \ Theta Band (degrees)	< -75		-75 : -45		-45 :-15		-15 : 15		15 : 45		45 : 75		75: 105		105 : 135		> 135	
< -75					617		618		619		716							
-75 :-45	605		658	(98)	681	(84)	676	(92)	685	(95)	681	(74)	649	(69)	665	(111)		
-45:-15	734	(112)	713	(87)	685	(72)	663	(65)	677	(71)	705	(72)	737	(60)	769	(63)	770	(75)
-15: 15	831.97		702	(75)	675	(64)	653	(66)	645	(70)	687	(63)	722	(49)	766	(68)	790	(74)
15 :45			682	(70)	670	(57)	644	(59)	639	(64)	686	(58)	724	(53)	769	(61)	792	(63)
45 : 75	796.47		703	(91)	668	(72)	651	(69)	660	(71)	681	(78)	716	(74)	748	(56)	752	(59)
75 : 90	745	(40)	742	(36)	729	(21)	728	(27)	723	(32)	725	(29)	733	(33)	734	(41)	742	(46)
> 90																		

Table 7 Average median reach distance in each panel Mean(SD) Group: Symptomatic (n=6)

Phi Band (degrees) \ Theta Band (degrees)	< -75	-75 : -45		-45 :-15		-15 : 15		15 : 45		45 : 75		75: 105		105 : 135		> 135	
< -75				657	(30)	659	(28)	655	(24)	661	(32)						
-75 :-45		515	(158)	608	(43)	622	(69)	631	(73)	639	(88)	664	(95)	624	(56)	608	(0)
-45:-15		652	(22)	603	(62)	569	(75)	585	(77)	620	(78)	651	(42)	703	(76)	708	(32)
-15: 15		651	(26)	591	(47)	560	(51)	560	(68)	606	(72)	641	(61)	699	(73)	699	(34)
15 :45				597	(38)	564	(49)	576	(59)	608	(69)	634	(65)	681	(70)	691	(28)
45 : 75				604	(5)	619	(65)	623	(84)	617	(82)	618	(45)	637	(43)	674	
75 : 90																	
> 90																	

4.2.2 Tables of normalized reach distance

Table 8 Average normalized reach distance in each panel Mean(SD) Group: Young asymptomatic (n=10)

Phi Band (degrees) \ Theta Band (degrees)	< -75		-75 : -45		-45 :-15		-15 : 15		15 : 45		45 : 75		75: 105		105 : 135		> 135	
< -75			1.06	(0.14)	0.97	(0.03)	1.02	(0.11)	1.07	(0.16)								
-75 :-45	1.00	(0.08)	0.95	(0.06)	0.91	(0.04)	0.90	(0.05)	0.93	(0.08)	0.95	(0.09)	0.96	(0.06)	1.02	(0.08)		
-45:-15	1.02	(0.07)	0.91	(0.07)	0.86	(0.06)	0.83	(0.05)	0.85	(0.05)	0.91	(0.07)	0.94	(0.06)	1.00	(0.07)	1.04	(0.08)
-15: 15	0.91	(0.19)	0.90	(0.09)	0.83	(0.07)	0.80	(0.07)	0.81	(0.06)	0.87	(0.07)	0.91	(0.06)	0.98	(0.07)	1.03	(0.08)
15 :45	1.04		0.91	(0.09)	0.85	(0.08)	0.81	(0.08)	0.81	(0.08)	0.85	(0.08)	0.90	(0.07)	0.97	(0.08)	1.02	(0.07)
45 : 75	0.75	(0.00)	0.91	(0.14)	0.88	(0.10)	0.86	(0.09)	0.86	(0.09)	0.86	(0.09)	0.90	(0.07)	0.95	(0.07)	0.98	(0.08)
75 : 90	0.89	(0.10)	0.91	(0.09)	0.90	(0.07)	0.86	(0.12)	0.87	(0.12)	0.87	(0.12)	0.88	(0.10)	0.89	(0.12)	0.88	(0.14)
> 90																		

Table 9 Average normalized reach distance in each panel Mean(SD) Group: Age-matched asymptomatic (n=10)

Phi Band \ Theta Band (degrees)	< -75		-75 : -45		-45 :-15		-15 : 15		15 : 45		45 : 75		75: 105		105 : 135		> 135	
< -75					0.85		0.85		0.85		0.93							
-75 :-45	0.83		0.86	(0.10)	0.88	(0.08)	0.88	(0.10)	0.89	(0.10)	0.89	(0.09)	0.85	(0.09)	0.88	(0.14)		
-45:-15	0.95	(0.10)	0.92	(0.10)	0.90	(0.10)	0.88	(0.09)	0.89	(0.08)	0.93	(0.11)	0.97	(0.09)	1.02	(0.09)	1.01	(0.08)
-15: 15	1.05		0.92	(0.11)	0.89	(0.08)	0.86	(0.07)	0.85	(0.08)	0.91	(0.10)	0.95	(0.08)	1.01	(0.09)	1.03	(0.09)
15 :45			0.90	(0.09)	0.88	(0.06)	0.85	(0.06)	0.84	(0.08)	0.91	(0.09)	0.96	(0.08)	1.02	(0.08)	1.05	(0.08)
45 : 75	1.00		0.89	(0.11)	0.87	(0.08)	0.86	(0.09)	0.87	(0.09)	0.90	(0.11)	0.95	(0.11)	0.99	(0.09)	0.95	(0.08)
75 : 90	0.92	(0.08)	0.92	(0.08)	0.90	(0.05)	0.92	(0.05)	0.92	(0.06)	0.91	(0.06)	0.92	(0.06)	0.92	(0.08)	0.92	(0.08)
> 90																		

Table 10 Average normalized reach distance for each panel Mean(SD) Group: Symptomatic (n=6)

Phi Band (degrees) \ Theta Band (degrees)	< -75	-75 : -45		-45 :-15		-15 : 15		15 : 45		45 : 75		75: 105	105 : 135		> 135	
< -75				1.04	(0.05)	1.05	(0.04)	1.01	(0.07)	1.05	(0.05)					
-75 :-45		0.77	(0.32)	0.88	(0.09)	0.89	(0.09)	0.91	(0.09)	0.90	(0.12)	0.95	(0.12)	0.89	(0.05)	0.80
-45:-15		0.99	(0.07)	0.86	(0.11)	0.82	(0.11)	0.84	(0.11)	0.89	(0.11)	0.95	(0.09)	0.99	(0.07)	1.00
-15: 15		1.03	(0.04)	0.85	(0.09)	0.81	(0.07)	0.81	(0.10)	0.88	(0.09)	0.94	(0.10)	1.00	(0.10)	1.04
15 :45				0.87	(0.06)	0.81	(0.06)	0.83	(0.06)	0.88	(0.09)	0.92	(0.09)	0.98	(0.08)	1.04
45 : 75				0.92	(0.06)	0.90	(0.05)	0.91	(0.07)	0.89	(0.09)	0.93	(0.09)	0.95	(0.07)	0.99
75 : 90																
> 90																

4.3 Comparison of coordinate systems MRE

Collected three dimensional kinematic data of the maximum reach envelope was first expressed as three dimensional Cartesian coordinates (X, Y, Z) with respect to a global coordinate system (CPSAM station). These three dimensional values were then translated to reach vectors with respect to the initial static position of the acromion and then converted to reach vectors. The Cartesian coordinates were converted to both cylindrical (R, θ, Z) and spherical (R, θ, ϕ) coordinate systems (all translated with respect to the local coordinate system of the acromion).

Each subject produced approximately 3600 data points for these coordinate systems consisting of concatenated front and side facing trials. The cylindrical and spherical coordinate systems were paneled in regions or bands of the MRE. This process was previously outlined in the analysis section of the report methodology (refer to Chapter 3.6) and a representation of the Cartesian coordinates of one person from each of the participant groups is shown in Figure 8.

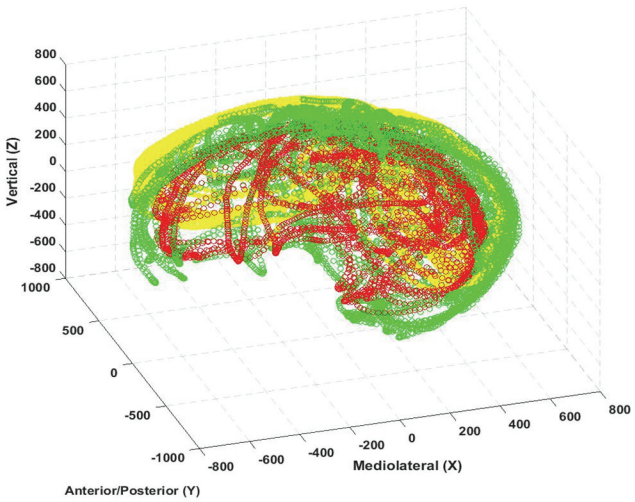


Figure 8 Data point cloud for 3 participants: green= young asymptomatic, yellow = age-matched asymptomatic, red= symptomatic

The two coordinate systems and their respective paneling methods were displayed as colour maps of the regions of the MRE. A comparison between the cylindrical panels and the spherical panels of the young asymptomatic cohort is shown in Figure 9. This group was chosen to complete this comparison as they had the largest reach area and distances. The cylindrical panels capped off the MRE with maximum and minimum heights (+ 500mm, and -500mm above or below acromial level) Where in the spherical coordinates phi was paneled into degree increments about the mediolateral axis of the acromion in the sagittal plane. These phi increments created a larger range of panels in comparison to the cylindrical panels. In Figure 9 there is a black fixation point to denote approximately where the acromion would be positioned if the MRE was flattened to a two dimensional image. Focusing on the number of participants able to reach into any given panel, there is consistency across both coordinate systems with the cut offs included. The spherical paneling had a larger periphery that would have been cut off in the cylindrical paneling method. The spherical paneling was more sensitive in detecting differences among the periphery in the asymptomatic group. This is displayed by the variability in the number of participants reaching in phi >75 and < -45 degrees in the bottom image of Figure 9. Moving forward with the remainder of

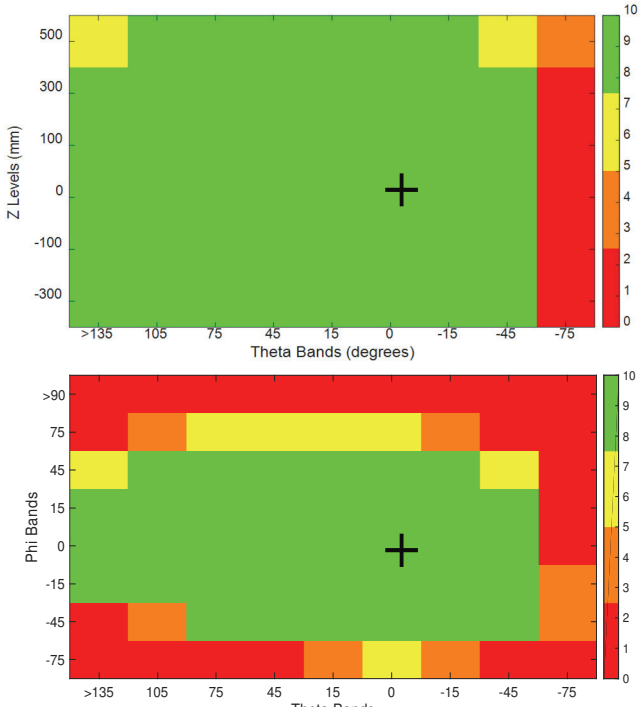


Figure 9 Cylindrical panels (top), spherical panels (bottom) for the young asymptomatic group. Colour bar represents the number of participants able to reach into a given region. + denotes an approximate position of the acromion

the analysis the spherical coordinate system was used to make comparisons, analysis and logistic prediction.

4.4 Analytic techniques in comparing the MRE between and within groups

4.4.1 Reach maps

The overall shape and area of the MRE was created through contingency tables of the panels of the MRE. If a person was able to successfully reach into a panel (there was at least one reach vector created in that panel) a dummy variable was coded as 1, however, if someone was unable to reach into a panel (no data available) the variable was assigned a 0. For the 72 panels of the spherical map of the MRE contingency tables were produced for the 0 Kg load condition between each symptomology group. Figure 10 displays a colour map of the contingency table outcomes. This method of colour coding was assigned by the number of participants successfully able to reach to a given panel.

In the figures of the colour maps, it was evident that distribution of panels that groups could reach decreased with age and injury, and with an increase in load. With the symptomatic group having the smallest number of reached panels and the greatest variability.

The outputted panelled data for each subject was then used in comparing the coordinate systems. The cylindrical system divided the sagittal plane of MRE into absolute 6 Z levels (heights) above and below in the acromial level, and divided the transverse plane into 9 angular (theta) positions about the acromial position. Negative theta angles refer to the side positions, and negative phi angles refer to the below acromial level positions. A dummy coded variable of Reach was used to code whether or not someone reached a specific panel of phi and theta. If a participant reached a panel of the MRE (had a calculated reach distance) the dummy variable was assigned a value of 1,

if a participant did not reach (no reach data) the variable was assigned a 0. Colour coded reach maps were created to outline the group characteristics of the MRE reach area. Using the dummy variable, a contingency table of the number of participants who reached (value of 1) a panel was combined by each injury group and load condition. The colours were set into 25 % portions of the number of participants able to reach a panel – Red < 25%, Orange <50% Yellow 50-75%, Green 75-100%. These visual maps were helpful in identifying patterns to complete statistical analyses. Areas that 25 % or less of the young asymptomatic group was unable to reach to were excluded. Phi bands 1 and 8 (<-75 degrees and >90 degrees) and theta band 1 (<-75 degrees) were two excluded bands.

On page 55 there is a grid of colour maps for each group, by load condition. The colour bar references the number of participants able to successfully reach into a given panel. The percentage of participants able to reach to all the panels decreases as injury is added, and as load increases. The 1.0 Kg load decreases the reach profile for each group.

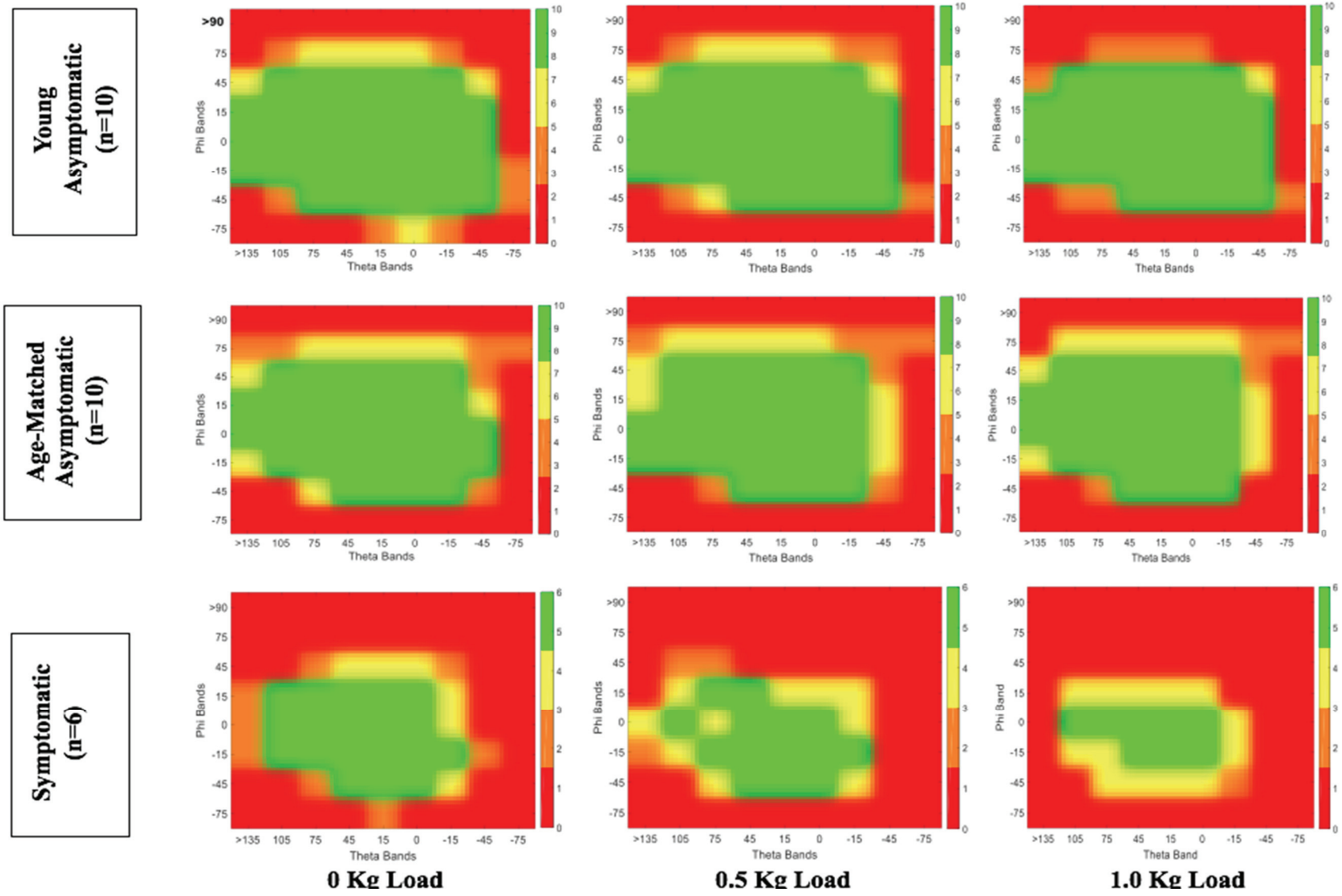


Figure 10 Colour maps for all group and load condition

4.4.2 Multivariate analysis

Initial objectives of this research included determining statistical/mathematical methods of distinguishing patterns within and between reach envelopes. Hypothesized methods included general linear models (GLM), logistic regression, and principal component analysis (PCA). While these methods were explored, GLM was used as the method of comparison reach distance of the MRE. A proof in principle logistic regression was used to investigate reach area of the MRE. With the current data set-up PCA was not included in comparative analysis due to assumption violations. However, an exploratory PCA was completed and included in the Appendix E to demonstrate is potential application in reach research.

4.4.3 Statistical models and the MRE

As highlighted in the first objective, the MRE was converted into 3600 data points in spherical coordinates, which was further reduced to panelled data of phi and theta. Within each panel the number of data points, mean, median, and standard deviation of the reach distances were determined. The median distance was used as the best measure of central tendency due to variability within a panel, and the range of the number of data points within each panel. A general linear model ANOVA was used to test main effects and interaction on the median reach distance between the 3 participant groups within the MRE. The median reach distance was the outcome dependent variable in all versions of the GLM. The main effects were participants, group, load condition, phi band, theta band. A full factorial model was created including main effects, and interactions. The objective of these models was to determine factors that affected reach distance.

Prior to completing the general linear model (univariate Analysis of Variance ANOVA), normality testing of the median reach distance for each participant group was

completed. All participant group data was found to violate the assumption of normality (Symptomatic group: Kolmorgorov-Smirnov (KS)= 0.54, $p<.05$; Age-matched asymptomatic group KS=0.34, $p<.05$; Younger asymptomatic group KS = 0.31, $p<.05$). Further observation into the normality Q-Q plots displayed the small tails of the data (maximum and minimum reach distances) were causing the violation of normality. The general linear model at its most basic level is a robust omnibus test to assumption violations. The residuals of the model were used as a better indicator of confidence in the model. The residuals produced a normal distribution after fitting the models and is displayed in greater detail in Appendix D.

GLM Model 1 (Absolute Reach Distance)

The first model included the dependent variable of absolute median reach distance (R) for each subject in each panel, and force entered predictors (number of levels) of participant (26), injury group (3), load condition (3), phi band (8) and theta band (9). This ANOVA included significant main effects of participant, injury group, load, phi and theta. GLM General Equation:

$$\overrightarrow{Reach\ Distance}_{R} = \text{Intercept} + \text{Participant}\,(26) + \text{Group}\,(3) + \text{Load}\,(3) + \text{Phi}\,(8) + \text{Theta}\,(9) + \text{Error} \quad \text{[Eq'n 4]}$$

This model had a good fit to the data with an adjusted R^2 value of 0.799. The model had several missing cases specifically in the symptomatic group, theta 1 and phi 7, 8, which was also highlighted in the colour map section of the results. These missing cases were areas of the envelope that participants were unable to reach. This model highlighted that the largest significant effect on reach was individual participant differences ($F_{(23,\ 2568)=}261$, $p<.001$). This main effect was expected to be large due to

variability in where each participant could reach. Acknowledging that the panels with missing cases was a limitation in this model it was determined that this model be revisited due to subject variability and missing cases due to the panels participants were unable to reach.

GLM Model 2 (Absolute Reach Distance Revised)

Referring to Section 4.5.1 Reach Maps and the missing cases in GLM 1, it was evident that some areas of the reach envelope were inaccessible for the participant groups. In specific, phi band 8 was not accessed across all groups. In completing statistical analyses these unreached panels would not return any values as the analysis would exclude the missing data panel-wise. A revised GLM was completed with the removal of the panels in 25% or fewer observations were available across the groups (in theory there should have been 78 observations for each panel 26 participants x 3 loads if all participants reached into a given panel). Another revision to address individual variability was the addition of a nested variable, where each participant was not entirely independent as they each belonged to a specific group. Participants were nested within the group they were part of (young, age-matched, or symptomatic). Equation 4 displays the revised model with bold font displaying revisions:

[Eq'n 4] $\underset{R}{\rightarrow}$ *Reach Distance* = Intercept + **Participant** **Nested by Group** **(26)** + Group (3) + Load (3) + **Phi (7)** + **Theta (8)** + Error

Table 11 displays the output for the ANOVA testing main effects of the adjusted factor levels of injury (3), load (3), phi band (7) and theta band (9). In this analysis there were greater amounts of non-missing cases and therefore increasing the homogeneity of

error variances (Levene's $F_{(374, 2008)} = .979$, $p = .597$). Participants were nested within the group factor in order to complete this analysis. This model was accepted for predicting the absolute reach differences, but normalizing the reach distance was hypothesized to be one way of minimizing the variation due to inter-participant differences. Therefore, a third model was created. The significant effects were the same between this model GLM2 and the upcoming model GLM3. GLM 3 will report the findings.

Table 11 General linear model ANOVA reach distance, bolded are significant findings p<0.05

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared	Observed Power
Corrected Model	13880883.150	143	97069.113	47.658	**0.000**	0.722	1.000
Intercept	124557006.786	1	124557006.786	61153.456	**0.000**	0.959	1.000
Subject (Group)	7211138.255	23	313527.750	153.932	**0.000**	0.575	1.000
Group	255158.646	2	127579.323	62.637	**0.000**	0.046	1.000
Load	83942.953	2	41971.477	20.607	**0.000**	0.015	1.000
Phi	84889.666	6	14148.278	6.946	**0.000**	0.016	1.000
Theta	1163437.428	8	145429.679	71.401	**0.000**	0.179	1.000
Group * Load	38373.136	4	9593.284	4.710	**0.001**	0.007	0.953
Group * Phi	152636.769	11	13876.070	6.813	**0.000**	0.028	1.000
Group * Theta	53087.978	15	3539.199	1.738	**0.038**	0.010	0.931
Load * Phi	57206.407	12	4767.201	2.341	**0.006**	0.011	0.966
Load * Theta	17836.901	16	1114.806	0.547	0.923	0.003	0.385
Phi * Theta	709835.206	44	16132.618	7.921	**0.000**	0.117	1.000
Error	5338437.684	2621	2036.794				
Total	1244728964.907	2765					
Corrected Total	19219320.836	2764					

GLM Model 3 (Normalized Reach Distance)

The arm length of each participant was measured in the anthropometric portion of the data collection. These measures were used to normalize the absolute reach distances $proportion\ R_{norm} = \frac{R_{absolute}(mm)}{Arm\ length\ (mm)}$. The same GLM was completed as in model 2, with main effects of injury (3), load (3), phi band (7) and theta band (9). With the normalization this model was estimated to be one of the better methods of analyzing main

effects, interaction effects and interpreting differences in the reach envelopes. Table 12 displays the ANOVA output for the between group effects.

Table 12 General linear model ANOVA output for normalized reach distance, bolded are significant findings $p < 0.05$

Source	SS (Type III)	df	Mean Square	F	Sig.	Partial η^2	Obs. Power
Corrected Model	19.509[a]	406	.048	12.775	**.000**	.695	1.000
Intercept	720.627	1	720.627	191591.884	**.000**	.988	1.000
Subject(Group)	8.526	23	.371	98.560	**.000**	.499	1.000
Group	.114	2	.057	15.177	**.000**	.013	.999
Load	.191	2	.095	25.357	**.000**	.022	1.000
Phi	.154	5	.031	8.189	**.000**	.018	1.000
Theta	2.416	7	.345	91.776	**.000**	.220	1.000
Group * Load	.066	4	.016	4.380	**.002**	.008	.936
Group * Phi	.196	9	.022	5.788	**.000**	.022	1.000
Group * Theta	.082	14	.006	1.564	.082	.010	.879
Load * Phi	.036	10	.004	.952	.484	.004	.515
Load * Theta	.017	14	.001	.330	.990	.002	.211
Phi * Theta	1.036	35	.030	7.869	**.000**	.108	1.000
Group * Load * Phi	.113	18	.006	1.668	**.038**	.013	.952
Group * Load * Theta	.064	28	.002	.610	.946	.007	.600
Group* Phi * Theta	.160	59	.003	.720	.947	.018	.920
Load * Phi * Theta	.084	69	.001	.322	1.000	.010	.517
Group * Load * Phi * Theta	.143	107	.001	.354	1.000	.016	.722
Error	8.557	2275	.004				
Total	2233.628	2682					
Corrected Total	28.066	2681					

There were no differences in the main or interaction effects between both the absolute and normalized reach models. However, the absolute model had a slightly better fit (adj $r^2 = 0.71$) in comparison to the normalized model (adj. $r^2 = 0.68$). The normalization of the data by arm length did not impact the significant factors on reach distance.

The normalized reach value model was used to interpret and display differences in the factors affecting reach. Main and interaction effects were tested using Bonferonni post-hoc comparisons when equal variances were assumed (corrected alpha significance level adjusted by number of pair-wise comparisons; dependent on number of factor levels). Overall participant variability was evident as the main effect of participant nested by group was significant with a large effect size ($F_{(23, 2275)}$= 98.5, p<0.001 η^2 = 0.499). There was significant difference in the mean normalized reach between the participant groups $F_{(2, 2275)}$= 15.2, p < 0.001 η^2 = 0.013). There was a significant effect of load on normalized reach distance ($F_{(2, 2275)}$= 25.4, p < 0.001, η^2 = 0.022). There were significant effects of position: phi ($F_{(6, 2275)}$= 8.19, p < 0.001, η^2 = 0.018) and theta ($F_{(7, 2275)}$= 91.8, p < 0.001, η^2 = 0.220).

Significant interactions affecting the average normalized reach distance included: group by load ($F_{(4, 2275)}$= 4.38, p = 0.002, η^2 = 0.008), group by phi ($F_{(9, 22758)}$= 5.79, p < 0.001, η^2 = 0.022), phi by theta ($F_{(35, 2275)}$=7.87, p < 0.001, η^2 = 0.108) and a three way group by load by phi interaction ($F_{(35, 2275)}$=1.67, p=0.038, η^2 = 0.013).

Achieved power of the significant main and interaction effects were all high (> 0.9). Interaction effects of position in the MRE and load were not all significant and had varying levels of achieved power.

Main Effect of Group

In addressing objective 3 of this study (comparing MRE between groups) the main effect of group was first assessed individually without interactions. A one-way ANOVA was completed to determine differences in normalized r between the 3 groups. Due to the groups sample size differences, the Levene's test was significant (p <0.05). Therefore, Games Howell unequal variances post hoc were used for multiple

comparisons between the mean normalized reach distance of the younger asymptomatic group and the age-matched asymptomatic group (t=6.45, p<.001) There was also a significant difference between the younger asymptomatic group and the symptomatic group (Games-Howell unequal variances t=4.62, p<.001). However, there was no significant difference between the symptomatic and the age-matched controls (Figure 11). This main effect addresses objective 3 of this report in that there is a difference in reach distance between certain groups. There were also interaction effects that involved the participant group factor, which will be explained in greater detail.

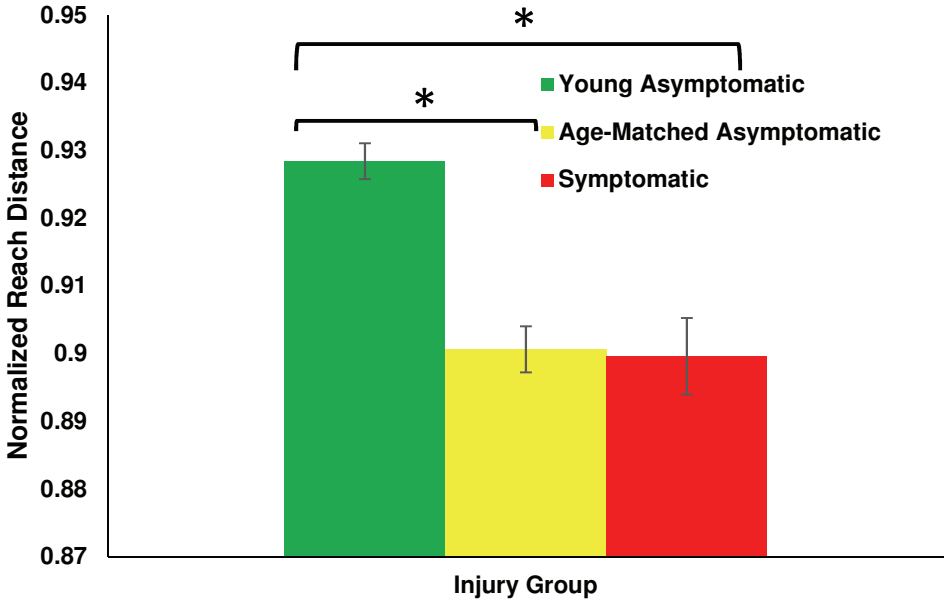


Figure 11 Main effect of group on reach distance * denotes a significant difference between groups p<0.001

Main Effect of Load

Bonferonni post hoc comparisons were used to identify which load conditions produced significantly different mean normalized reach distances. There was a significant difference in the mean normalized reach of 33mm between the 0.0 Kg (no load) condition and both loads (p<.001 for both comparisons). However, there was no

significant differences between the two load conditions (p=.471). Figure 12 displays the mean reach distances for the load conditions.

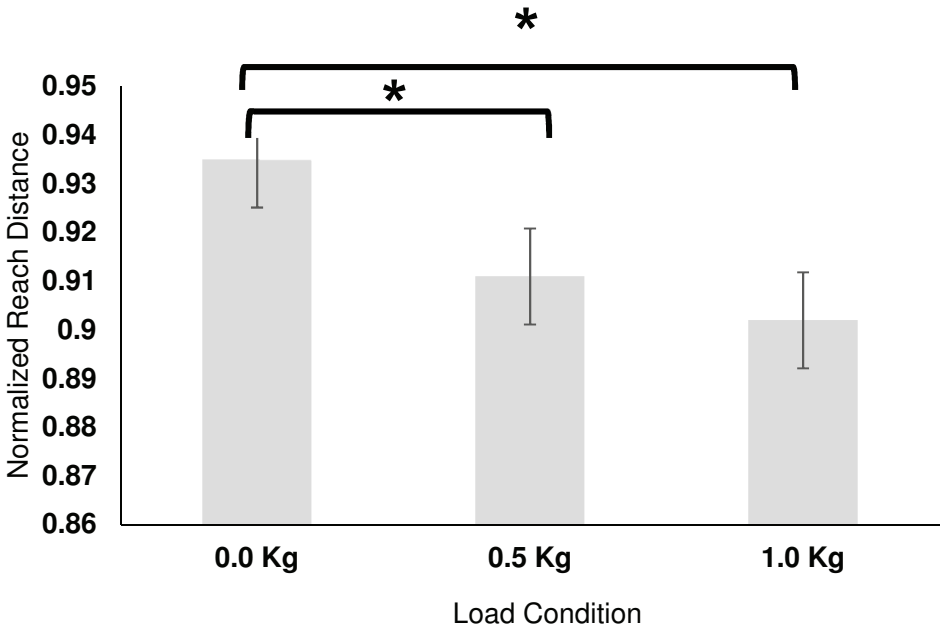


Figure 12 Main effect of load on the mean (SE) of the normalized reach distance. * denotes a significant difference between load conditions p<0.001

Interaction effects (Group, Load, ϕ & θ)

The previously described effects were directly related to questions of this investigation, however the produced interaction effects were a significant finding to understanding the MRE. Figure 14 displays the interaction of group and load condition. The young asymptomatic and age-matched asymptomatic groups both had a greater reach distance with no load (0.0 Kg) and decreased dramatically with either of the load conditions. The symptomatic group began with a decreased reach in comparison to the other groups, which was not affected by the 0.5 Kg load, but significantly decreased with the 1.0 Kg load (Figure 13).

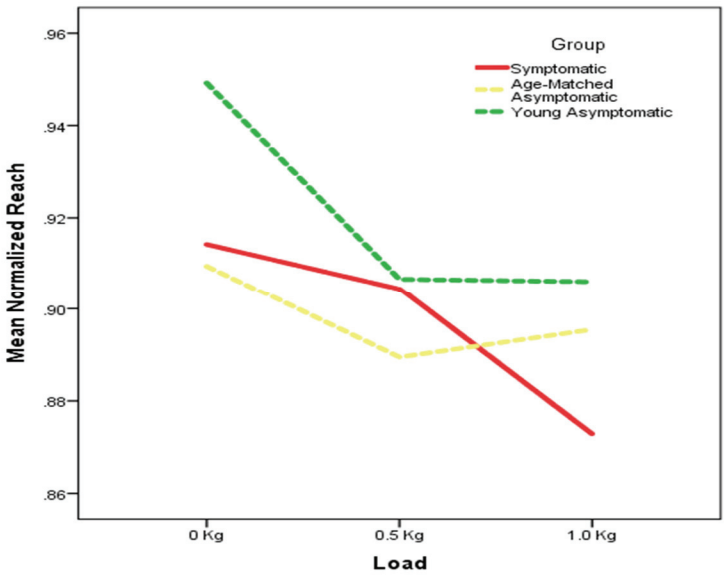


Figure 13 Interaction plot of group and load condition where 0 = 0.0 Kg, 5= 0.5 Kg, and 10=1.0 Kg

The effect of panels within the reach envelope was compared using Bonferonni post hoc comparisons. There were significant differences in the panels in both the phi and theta positions, yet these variables were not independent of one another. This made interpretation of the results difficult. Figure 15 displays the panel interactions, where the periphery (outside thetas to the right of a person and across the body) had varying reach distances dependent on the phi level. Reach distance was largest in the periphery of theta, and decreased while directly reaching in front of the person. This was not the case for the highest phi band (>45 degrees above acromial level or the lowest phi band – 75 degrees). Referring to the colour maps previously described, there were very few symptomatic participants able to actually reach into high phi bands explaining the interaction. The interaction of the lowest phi level by theta, displayed by a blue shortened line in Figure 15 was a factor of seated position. Where there were reach distances up until 45 degrees in theta and then there is no longer any data. This represents reaching directly in front and across the body, which would be where the knees would be located (therefore un reached in the collection).

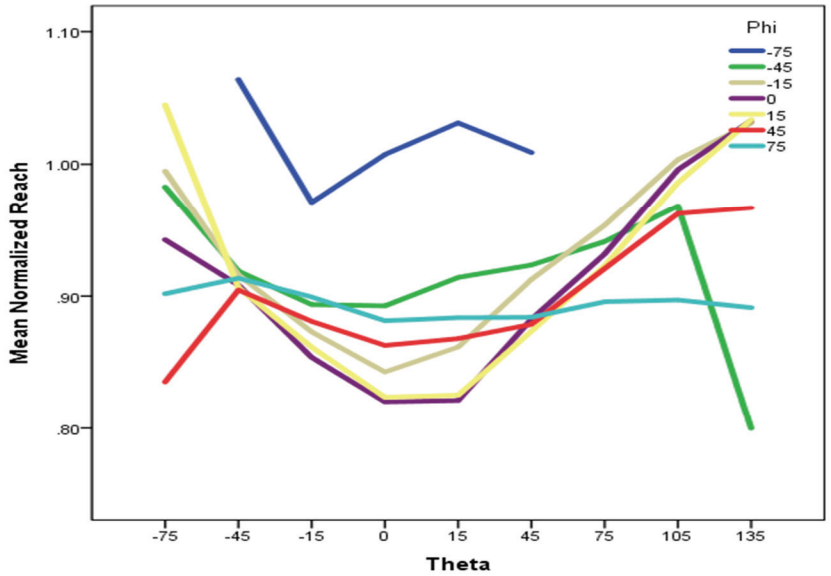
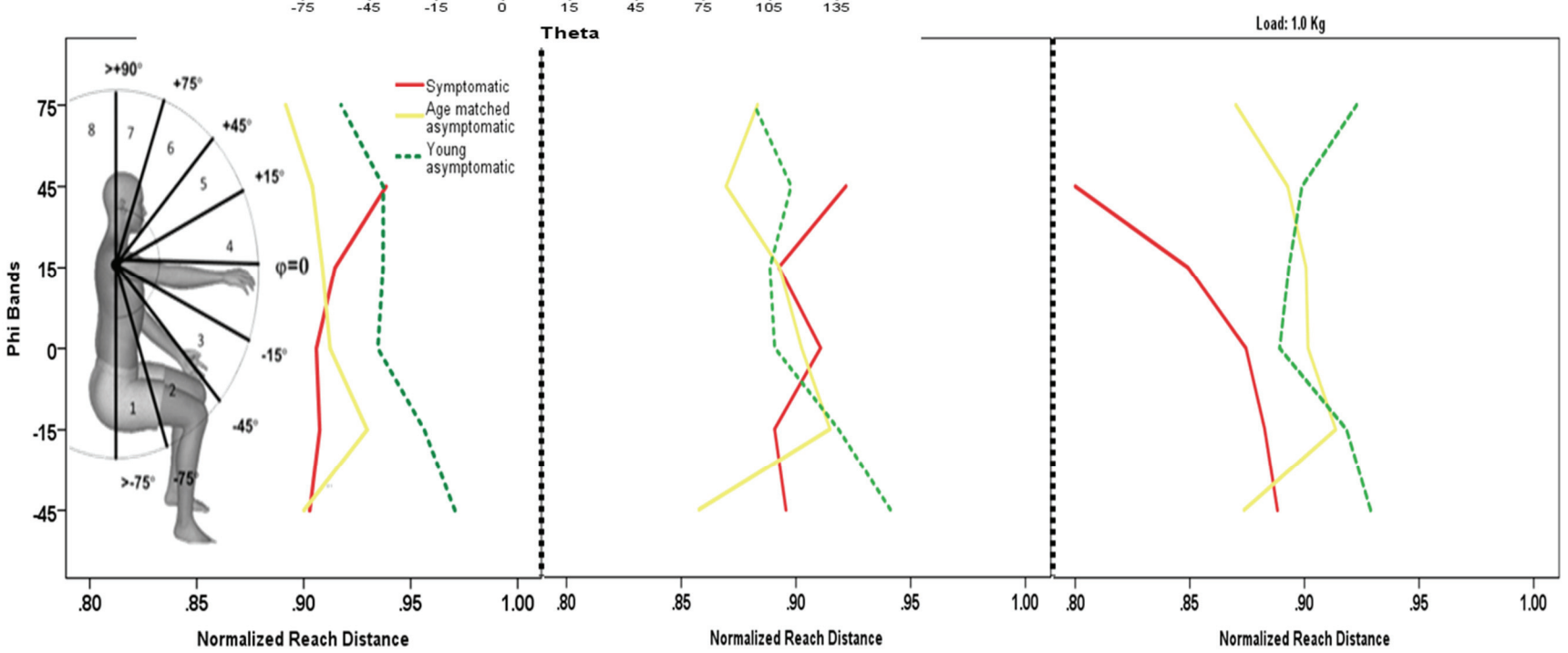


Figure 14 Interaction plot between phi bands and theta bands where band 1 is the smallest (<-75 degrees) up to band 9 (>135 degrees). (Left)

Figure 15 Three way interaction of Group, Phi and Load. The reader should note the axes are flipped to demonstrate the phi levels, normalized reach increases in the + x direction. (Below)



4.5 Predicting reach outcomes *proof of principle*

The previous outcomes of the GLM and factors affecting reach looked solely at distance of reach in spherical coordinate system. A subset of comparing reach between groups was to identify *where* (areas) that participants could reach. The parametric statistics previously described excluded data where participants could not reach. Whereas missing data (unreached panels) were still valuable information and needed a method of comparison. These values were not assigned a value of 0, because that would represent a reach distance of 0 mm which in fact was not true in a panel, it was simply that the subject did not have a value. Similar to the approach of the colour maps (Section 4.5.1) if a person was able to successfully reach into a panel (there was at least one reach vector created in that panel) a dummy variable was coded as 1, however, if someone was unable to reach into a panel (no data available) the variable was assigned a 0. This set up created a binary categorical variable as a dependent outcome measure. A logistic regression was performed to assess what factors influenced where a person or group could reach. The objective of these models was to determine factors that affected reach area within the MRE.

A binary logistic regression with dependent variable of "*did the participant reach the panel? (Yes or No)"* coded as 1=yes and 0 = no was used with predictors of arm length (continuous), injury, load, phi and theta was performed using the spherical coordinate system. All phis and thetas were included in this analysis compared to the GLM, because it absolved the issue of missing data. Table 13 displays the regression output including the predictors of group, load, phi and theta. As a proof of principle this analysis was set forth to address the factors affecting reach area, and provide a preliminary step towards creating prediction models. The panels of reach data are not

orthogonal or independent of one another and therefore pose a limitation into this analysis.

Table 13 Binary logistic regression table predicting reach panel success as binary outcome variable of yes (1) or no (0).

Sources	df	*Adj Deviance*	*Adj. Mean*	x^2	Sig	
Regression	17	2958	174	2958	**0.000**	*
Group	2	637	318	637	**0.000**	*
Load	2	27.2	13.6	27.2	**0.000**	*
Phi	6	2330	388	2330	**0.000**	*
Theta	7	541	77.2	541	**0.000**	*
Error	4348	*2831*	0.651			
Total	4365	5789				

A logistic regression model included the main effects of this investigation namely group and load condition. The panels of phi and theta were included as main effects as well, acknowledging the significant interactions and dependence between panels will create larger more robust analyses in the future. The reference levels of each factor were as follows: Young Asymptomatic, Load 0.0 Kg, Phi 1, and Theta 2. Phi 8 and Theta 1 were removed from this initial analysis due to the assumption of complete separation of the data. Where zero participants were able to reach into phi 8 (> 90 degrees above acromial level) and theta 1 (<-75 degrees to the right of their side), the data was completely separated because there was 0% probability that a person would reach into those panels. Equation 5 is the model of predicting probability that an event occurs.

[Eq'n 5]
$$P(Y) = \frac{1}{1 + e^{-(b_0 + b_1 X_{1i} + b_2 X_{2i} + \ldots + b_n X_{ni})}}$$

Where P(Y) is the probability that a participant will reach a panel (1), and Y' (Equation 6) is the equation in the denominator of equation 5 where set parameters can be entered.

[Eq'n 6] Y' = -4.139 + 0.0 (YASYM) - 0.524 (ASYM) - 3.004 (SYM)
+ 0.0 (0 Kg) - 0.3155(0.5 Kg) - 0.609 (1.0 Kg)
+ 0.0 (ϕ 1) + 4.196 (ϕ 2) + 6.957 (ϕ 3)
+ 7.009 (ϕ4) + 6.3 (ϕ 5) + 4.291 (ϕ 6) + 2.514 (ϕ 7)
+ 0 (Θ 2) + 2.018 (Θ 3) + 2.739 (Θ 4) + 2.848 (Θ 5)
+ 2.632 (Θ 6) + 1.867 (Θ 7) + 1.376 (Θ 8) -0.179 (Θ 9) + Error

As a best initial approach of this model, the fitted model did not have predicted probabilities that statistically differed from the observed probabilities (Pearson x^2 *(4348)* =4402, p=0.279). However, the model was only able to correctly fit approximately 50% of the expected probabilities (deviance $r^2 = 0.511$). None of the listed coefficients were highly correlated with one another (all VIF values < 4). Within the main factor of group, young and age-matched asymptomatic individuals were significantly more likely to successfully reach panels than symptomatic individuals with rotator cuff tears (OR= 20.16, OR=11.94, respectively). Load was a significant factor however; the odds rations were all below 0.8 making low odds that a specific load condition would highly affect the overall area of reach.

In creating a prediction model it was appropriate to validate the model. The model was validated using a split-sample approach (Steyerberg et al., 2001). With a small sample of data 80% of the participants remained in the model and 20% were removed. The logistic regression was recreated with 20% of participants removed, and the percent agreement between their data and the predicted probability was calculated. There was 1 participant removed from the symptomatic group and 2 from each of the asymptomatic groups. Validating the model by predicting the removed participants' data, it was found

that for the symptomatic participant there was 70 % agreement between the predicted probability of reaching panels, and the observed occurrence of reaching a panel. For the removed age-matched asymptomatic participants there was 95% agreement for the young participants and 84% agreement for the age-matched individuals. Looking at the reach envelope colour maps, the larger amount of agreement for the asymptomatic group was attributed to less variability. The younger group (only 84% agreement) had larger variability in the periphery where some but not all participants were able to successfully reach into higher phi bands than those in the age-matched asymptomatic group.

CHAPTER 5 DISCUSSION

This project was a starting point to quantify the MRE and its applications as a measure of reach. Referring back to the adapted ICF of shoulder injury, potential applications of this research fall into the categories of both prevention and intervention. The measurement aspect of the MRE is a well-documented area within industrial design literature, but is novel to clinical applications. The participant groups targeted in this investigation (rotator cuff tears) are a new group in the database of MRE measurements. To the best of the author's knowledge no previous research has investigated the MRE on a clinical population with rotator cuff tears, nor is there a gold standard for 3 dimensional assessment of shoulder injury. Previous measurements groups include male and female operators (Sengupta & Das, 2000), spinal cord injury and wheel-chair users (Kozey & Das, 2004), and now the new addition of rotator cuff injuries. The ergonomic application of this research is one large aspect, where the measurement of the MRE was quantified for a new group of individuals. The clinical application of this research was another aspect with support from ergonomics and biomechanics. The long-term goal of this research is that the database will be built upon to create a comprehensive functional assessment tool for shoulder injuries. This goal is beyond the expertise of one research project and will involve multiple disciplines in future investigations. This research will present a useful measurement (MRE), methods of comparison and analysis, and factors that affect reach in a small participant cohort. Ultimately these findings will be combined with the expertise of knowledge translators, clinicians, rehabilitation specialists and many others to determine the most effective way to incorporate a new measurement in clinical assessment.

5.1 The study populations

Previous research of the reach envelope of young individuals was used to provide a self-reported uninjured young asymptomatic population. The age similar group was approximately 10 years younger than the symptomatic group, mainly due to an adult male in this study group who was mid 30s. This decreased the age-simliar properties of the groups but highlighted the need for larger groups sizes, and future investigations into the selection of groups. Age and injury may not be the best method of group selection. The correlation of the presence of RCTs and age documented in the literature emphasized the need for an asymptomatic group that was not the previously collected young sample (Yamaguchi et al., 2006). The demographics of individuals with rotator cuff tears (RCT) were pulled from data collected in a Halifax Orthopaedic Clinic. The age-matched asymptomatic group completed a self-report exclusion survey for previous shoulder injuries. However, current clinical assessment techniques include the use of the Western Ontario Rotator Cuff (WORC) Questionnaire and the Disabilities of the Arm, Shoulder and Hand (DASH), which may have provided a better screening process of the asymptomatic individuals. These surveys are currently completed by RCT clients of the clinician, and should be included in future studies. The symptomatic population was recruited through the team at the Orthopaedic Clinic in Halifax. The calculated strata of demographics given prior to data collection suggested a large amount of males than females with rotator cuff tears (RCT). However, an equal number of male and female participants were recruited. Initially a sample size of 10 participants was expected, however, due to low recruitment only 6 were recruited during the timeline. This research will continue with collection to address a larger project goal 20 RCT participants in total. Even though only 6 participants were recruited, the achieved power of the statistical

difference in reach distance and normalized reach distance was high (1.00). The effect size of this difference was between a small and medium effect partial $\eta^2 = 0.03$ (Cohen, 1988). With the achieved power and calculated effect size, the difference due to subject groups was meaningful in interpreting the results. However, fine details within load interactions in the reach envelope may require larger study populations as the achieved power of these non-significant findings were quite low (<0.5). Future studies incorporating a larger sample size would influence the effect sizes of the significant findings and strengthen the confidence in the interaction characteristics of load, and position in the MRE.

5.1.1 Anthropometry

Eight anthropometric measures (Age, Height, Weight, Seated Height, Seated Acromial Height, Seated Elbow Height, and Arm Length) were collected in this investigation. The majority of these measures are applicable to ergonomic design as they contribute to key dimensions highlighted by Das & Sengupta (1996). Posture, work height, normal and maximum reach areas, clearance (head and lateral), and visual requirement were identified as key dimensions to accommodate the majority of a population in design (Sengupta & Das, 1996). Chaffin and colleagues presented data in trajectory reaching tasks that suggested, posture and age had some of the greatest influences on reach. (Chaffin et al., 2000).

Arm length was a measurement of particular interest for interpreting any absolute differences between groups. If the participant groups had significantly different arm lengths this could have in turn affected the absolute reach differences. However, there was no difference in the average arm lengths between the 3 groups, which did allow for comparison in absolute reach distance. All of the participants but one symptomatic

participant self-reported a dominant right arm as indicated by the inclusion/exclusion criteria. The individual with the left arm RCT was still included in the analyses but the data was mirrored to create a right hand envelope for the current comparison.

Current ergonomic literature does differentiate the left versus right arm in reach envelope measurement or application. It assumes that the left arm creates a mirrored envelope of the right arm (Konz & Johnson, 2000). This is without a doubt a major limitation moving forward, especially translating this measurement into clinical practice. While the method of measurement would remain the same for the left arm there are many physical factors that could create discrepancies in reach between right and left, or dominant and non-dominant arms. Strength, musculature, hand dominance are all factors that will need to be considered in future MRE research.

5.1.2 Clinical Measures

The measured ROM measures of the asymptomatic age-matched cohort were similar to those reported in the literature (Soucie et al., 2011). The differences between the asymptomatic group and symptomatic group were in the abduction measures (active and passive) and passive external rotation. In these specific planes of motion in goniometer measuring, the symptomatic participants on average were not far from norms. However, the standard deviation displays a larger variability for the symptomatic group. There were differences in the strength measures of the asymptomatic and symptomatic groups (all significantly different $p < 0.05$). The strength measures were recorded post reach envelope collection, which may have induced small amounts of fatigue onto participants. The rationale for strength measures post collection was to provide a post load bearing task strength measures for the clinical team. An initial strength measure was taken in clinic for all symptomatic participants, and the collected measures were provided

to the clinical team. It was anticipated that strength would be significantly less in all directions for the symptomatic group. Rotator cuff pathologies, specifically those with muscle tears, experience less strength, due to damage onto the muscle (Murray et al, 1985). A decrease in endurance was subjectively quantified by researchers when certain symptomatic individuals were unable to complete a full 45 second length trial. The addition of a load for these individuals also decreased reach, suggesting strength is an important measure in understanding the MRE.

5.2 Comparing coordinate systems

Displaying the MRE in different coordinate systems posed advantages and limitations depending on the context and application of the measurement. As the MRE has foundation in ergonomics literature as a design measurement it was a first step to present the MRE as previous authors had (Das & Behara, 1998; Sengupta & Das, 2000). This first representation was a cylindrical coordinate system with reference to the acromion created from the collected Cartesian coordinates. From an industrial workspace design perspective, the measurement of a reach envelope presents useful dimensions as to the layout of a workstation and the occupational demands of an operator (Faulkner & Day, 1970). Sengupta and Das used the MRE to compare gender, and posture differences in workstation design using the cylindrical coordinate system (Sengupta and Das, 2000). The absolute cut-offs made for the Z height levels of the MRE were could present heights that could be implanted in industry workstations or in the design of workstations in daily life (ie. Countertop). Converting to cylindrical coordinates could be of interest in future research that looks at accommodation and design for individuals with injury, or returning to occupation post injury. This knowledge is of value in the design of workstations to

prevent injury such as rotator cuff tear, by creating workstations that decrease the load, repetition and moment about the shoulder joint.

It was noted that in any case of using cylindrical coordinate systems the reach vector (the direction and magnitude of where participants could reach) was calculated as a projection onto the corresponding Z level (Refer to Appendix B for converting coordinate systems). This projection is useful in design to outline that at high and low levels above and below the shoulder (or any reference point). However, the projection vectors do not make the reach distance relatable to arm length, and current clinical measures of range of motion, which use angular measurements.

Other methods of representing the reach envelope have included measuring arm length and creating dimensions based upon a spherical radius. Farley (1955) was one of the original investigators of the reach envelope, and used a radius of arm length to create a sphere MRE. Kozey and Mackenzie (2002) investigated this spherical modeling of the reach envelope. Their findings displayed that the MRE is not a perfect sphere, and that radial fit could only be used in the central areas of the MRE (Mackenzie & Kozey 2002). The periphery was not equivalent to the radial distance. Similarly, previous research has displayed that there were interactions of the angular position and height above and below the MRE that affected the total reach distance (Johnston et al. 2016).

With these considerations and the clinical application of this current study, the projection vector of reach (R) by θ, and Z did not directly address the objective of mapping reach for a symptomatic population. Nor did the cylindrical coordinate system fully answer to the concept of shoulder function. The spherical coordinate system representing the reach vector (R) as a factor of θ, and ϕ removed the projection issue previously highlighted. In this coordinate system the reach vector directly depicts a

position vector from the initial static position of the acromion through the end measured reach distance provided through CPSAM's motion capture. Paneling the data still created absolute cut-offs of the MRE, however, this coordinate system was chosen as a better fit to this project because:

a) The spherical coordinate system had greater sensitivity in the periphery of the MRE, determined by young asymptomatic participant variability in these panels, and the eradication of the absolute cut offs created by the cylindrical system;
b) It was better received and understood by a variety of audiences (clinicians, general population) since it represented angular measures, and no projection vectors;
c) This system better represented the motion of the glenohumeral joint reach, allowing participants to completely move through the periphery; and
d) This system was more relevant to current clinical measurement standards of relative goniometer angles of shoulder range of motion.

Though validity was not addressed in this investigation it is hypothesized that this system could have better context validity when compared upon the current standards in assessment of shoulder range of motion (goniometer measurements). Goniometer measurements present the range of motion in set planes such as the sagittal plane for flexion, where the relative angle from the scapular border through the joint line of the humerus is calculated (Norkin &White, 2016). One could compare a forward flexion measurement from a goniometer to the difference in maximum and minimum reach vectors located directly above and below the acromial position in any given sagittal plane of the MRE. This hypothesis presents a need for further investigation into the differences

between parsed MRE data and goniometer measurements. However, it does display the advantage of using the spherical coordinate system over the cylindrical coordinate system moving forward.

5.2.1 Normalizing reach data

The output of the current customized Matlab programs provides reach vectors in both cylindrical and spherical systems in absolute and normalized terms. In this research, normalizing was completed by arm length (defined as the distance from the acromion process to the middle phalange). By this equation, a proportion of 1 would be a measured reach distance to the arm length. It was important to highlight that with this normalized reach value it was not anticipated that asymptomatic individuals would always achieve a normalized value of 1. This is due to measure of arm length being defined from the acromion process to the middle phalange, whereas the measured r vector was the acromion process to the tip of the stylus in a pinch grip made by participants.

In the application of better understanding shoulder function this normalizing process targeted glenohumeral movement. The constraints of limiting trunk movement and elbow/wrist joint movement were asked of the participants. The association between shoulder ROM and the MRE was based upon a rigid assumption of the upper limb (rigid segment between the humerus, forearm, wrist and hand). This representation is still different from normalizing the reach envelope as a perfect sphere of arm length (Kozey & Mackenzie, 2002). The methodology of collecting the acromion position (local origin for the reach vector) was a static collection when the participant first began the reach collection. Therefore, throughout trials any acromial position movement through accessory structures was not accounted for or collected dynamically. While a limitation, the collection of gross movement of reach better reflects how an individual will

functionally complete maximal reaching motions. Even if producing reach requires some compensatory mechanisms for some individuals the MRE measure can present their outer limits of motion. Understanding and documenting the gross measure of reach will provide an absolute reference for research wishing to tease out specific joint synergies in upper limb movement.

The GLM models reported in the comparing reach section of the results, displayed significant main effects of each participant. This finding in the absolute reach data was anticipated due to the variability in arm length of participants. After normalizing the data, the main effect of participant was still significant. Normalizing the data posed an advantage for group comparison and removing individual differences. This was especially useful in removing any covariate effect due to gender. On average, females typically have a narrower shoulder breadth than males (Chaffin et al., 2000). Which is relevant in industrial design where reference points are typically made with respect to a table top or the body midline. This application of the MRE was focused on glenohumeral function, and therefore any anthropometric differences were avoided. The normalized MRE measures could then be generalized across the 3 participant groups, making a potential clinical assessment more feasible. However, there is documented literature to suggest that the glenoid shape is different between males and females (Merril, Guzzman, & Miller, 2009). In an anatomic study of 363 bone specimens, male glenoid bones were significantly greater in height and width than females, resulting in a rounder shape compared to an ovular shape for woman (Merril, Guzzman, & Miller, 2009). This factor, which may affect occurrence and limitation due to RCT, could have implications in reach. Sengupta & Das (2000) built upon early work completed by Faulkner and Day (1970) investigating female versus male operator reach envelopes in seated and standing

positions. They documented gender differences in absolute reach distance, with males having a 13.5% greater absolute reach distance (Sengupta & Das, 2000). The origin of these values was a fixed table reference point in comparison to the current use of a fixed acromion position. Women were unable to reach a height (Z level in cylindrical coordinates) of greater than 90cm above the table reference point where as men could (Sengupta & Das, 2000). The spherical coordinate system, and normalizing by arm length removed some of the issue of missing data due to gender differences. This process posed advantages and limitations. For many panels, the asymptomatic groups did not achieve a normalized reach value of 1.00. In theory, the participants should have been able to do so in Phi 3, Theta 4 (reaching directly out in front of them ≈ arm length). This was not the case as the position vector of reach was created as the static acromion process position to the tip of the stylus. This would decrease the reach vector in comparison to arm length, which was measured to the distal end of the middle phalange. However, this method of normalizing reduced any impact of anthropometric differences between genders (such as shoulder breadth) that would have affected reach distance.

5.3 Methods of analyses

A group of analyses were attempted to determine valid methods of reach envelope measurement between groups. With multiple models, additions and removal of predictors, observation and qualitative analysis this research presents that it may be necessary to have multiple methods of addressing the objectives from a scientific point of view. In the future, translating this measure (MRE) into practice in clinical settings will require an expert panel in comprehending the big picture of these analyses.

5.3.1 Models of the envelope

Models of the reach envelope were created for both general linear models (GLM) and logistic regression (LR). The GLMs were targeted to predict, and identify factors that affected reach distance. Whereas the LRs targeted those same factors for reach area. Arguably both distance and area are important for distinguishing difference between groups. This is one reason why the MRE as a volumetric measure provides greater value of information than a planar angular or distance measurement. However, it was difficult to find a statistical analysis that could account for both of these outcomes. This was primarily due to the fact that a panel where someone was unable to reach could not be assigned as a missing data point nor a value of 0. Most parametric statistical analyses require an assigned value to complete the tests, and or areas where the data was computed as missing, the tests would exclude these predictors.

In the previous reach investigations a GLM was performed to test the effect of load, Z level and θ region on the reach envelope (Johnston et al., 2016). This test determined that there were significant differences of approximately 6.5% reduction in the total reach envelope volume between the 0 Kg load condition and the 0.5, 1.0 Kg conditions. Seeing that the GLM was able to distinguish differences in load, it was hypothesized that the differences due to participant symptomology would be greater in magnitude and effect.

Logistic regression as a proof in principle analysis was an effective method of identifying factors that affected reach area. It also provided a method of creating prediction models for future consideration in using the MRE as a clinical diagnostic tool. Only main effects were included in this investigation in order to keep with an assumption

that all predictors were independent of one another. Main effects on reach area included the group, load, phi and theta panels (all statistically significant $p < 0.001$). The panels of the envelope or position within the MRE were main effects on both reach distance and area as highlighted by the GLM and LR models. However, it was assumed that these panels were independent of one another, when in truth the panels are highly dependent upon one another. Looking at the values of reach distance, the colour maps, or the attempted PCA analysis are clear indicators that panels of the reach envelope are related to each other. This provokes future investigation into methods of paneling the MRE, and statistical analyses that account for dependent data such as mixed models (Jaeger, 2008).

Utilizing logistic regression to create a prediction model was successful. This first proof in principle analysis predicted where a participant was probable to reach within the MRE given their affiliated group. As highlighted by equation 6 p. 68 in this report, one could predict the probability that an individual could reach to a given area of the MRE knowing their group (symptomatic, age-matched asymptomatic (older cohort), or younger asymptomatic) and the load they maneuvered. In validating this model using a split sample approach and removing 20% of participants from the model, there was high agreement in predicting reach area for the asymptomatic groups (95% for the age-matched and 84% for the younger) and less agreement for the symptomatic group (70%).

The concept of this model will be useful in the final application of the larger research aims. The model could be used to predict where are participant should be able to reach given their current diagnosis, where they should be able to reach post-surgery, and predict the target range of motion once fully rehabilitated post treatment intervention.

5.4 Comparing the MRE

5.4.1 Group differences

Throughout reach envelope data collection there was an evident discrepancy between the symptomatic group and the asymptomatic groups in terms of the overall movement for reach. The largest difference was the variability in overall movement of the symptomatic group. Some individuals mentioned they had lived with a rotator cuff for a period of time and had adapted their biomechanical mechanisms and compensatory movements associated with reaching tasks to reduce pain and discomfort. It was not uncommon to see a symptomatic individual increasing the contribution of scapulathoracic, and scapulahumeral rhythm in order to complete reaching trials. These motions were embedded in the measure of the MRE and not individually measured. Some participants were able to get above shoulder level in terms of a phi angle, whereas others were not. As a result of discomfort, full extension of the arm was not always possible for individuals even in the asymptomatic groups. Notes were made if the participant performed elbow/wrist flexion extension in order to complete the trial. However, consistent feedback was given to the participant if this occurred. Visually and through the reach map comparisons, the symptomatic group moved with greater variability specifically in the outer bounds of the MRE.

In describing the theta angular regions (reaching from the side to across the body), all participant groups displayed similar patterns. There was a significant interaction with the angular position and the phi band (height level) throughout the envelope. In sweeping across the reach envelope from the right side of the body through to reaching across the left side there was a consistent pattern for and motions completed about or below shoulder level. Normalized reach distance was largest in the periphery, (behind the right

side or reaching fully across the midline to the left side). The reach decreased by approximately 25% of the normalized arm length towards the centre of the MRE. This phenomenon was seen in previous research conducted on the reach envelopes of asymptomatic groups where fixed reference points were used to calculate reach vectors (Johnston et al., 2016; Sengupta & Das, 2000). When a participant would reach behind the right side, accessory motions such as translation and retraction of the scapula or depression of the clavicular joints were embedded into the measured reach distance. Similar in reaching across the body, scapular, thoracic, and clavicular motions may have facilitated reach distance. Since the reach vectors were calculated about the pre-measured static acromion position, it is logical that any of these compensatory mechanisms would increase reach distance. Deviation from the initial acromion position would add length to the calculated distance between the stylus pointer and the acromion position. While this could be avoided with dynamic tracking of the acromion position, such a measure would not have the added value of the contribution of the accessory motions. Future measures would benefit from the additional information provided by tracking positions of the scapula, sternum, and clavicle. However, these measures are timely and not easy to accomplish. Therefore, their inclusion could limit the feasibility that has been shown in using the MRE as a potential clinical tool.

There was a significant group effect on the reach distance distances between younger asymptomatic and both the age-matched and symptomatic groups. However, there was no significant difference between the age-matched asymptomatic and symptomatic groups. One hypothesis is the accessory motions that contribute to shoulder range of motion, such as scapular and clavicular movement, are used by the younger adult population more so than an older or injured population (Ludewig et al, 2004).

Individualized reach maps displayed that there were differences in which panels participants could reach. This was statistically confirmed in the logistic regression, where group was significant predictor on probability of reach. Young and age-matched asymptomatic individuals were significantly more likely to successfully reach panels within the MRE than symptomatic individuals with rotator cuff tears (OR= 20.16, OR=11.94, respectively). Interpreting these odds ratios with the previous information on reach distance displayed a larger finding. Age-matched asymptomatic and symptomatic individuals had similar reach distances (~ 0.89 proportion of arm length), which was significantly less than the younger cohort (~ 0.95). Alternatively, the probability of being able to successfully reach panels was 11.9 times higher for any age-matched asymptomatic individual compared to a symptomatic individual. Younger participants were only 1.7 times more likely to successfully reach a panel than the age-matched group. This suggests that age may affect reach distance more so than reach area, and symptomatic shoulder injury may impact reach area more so than reach distanceRotator cuff pathologies are known to create restrictions in range of motion and limit functional abilities (Bayder et al., 2009; Hall, Middlebrook, & Dickerson, 2011). The exact muscle or muscles that were torn within the rotator cuff were unknown in this study, but could greatly influence the variability in the range of motion. All participants were diagnosed with full thickness massive (> 3.0 cm) rotator cuff tear. These massive tears clearly impacted overall range of motion in this group, specifically the periphery of the MRE. As such, the MRE was successful as a measurement to be able to distinguish differences between asymptomatic and symptomatic pathologic shoulders. In the goniometer measures, there were only 2 significantly different range of motion measures (abduction and external rotation). However, the differing shapes of the MRE reach maps and the

findings of the logistic regression do determine significant differences in total reach between the two groups. In relation to these aforementioned range of motion measures (Section 5.1.2), there is a need for further understanding of three dimensional measurement of range of motion, in relation to current standard measures.

With the completed MRE motions there was room for compensatory movement to contribute to the overall reaching action. All groups were provided the same feedback and proprioceptive aids. For this investigation it was important to determine a gross measure of reach without the use of further constraints of human movement. Dynamic functional movement was reflected with minimal intrusion into an individual's reaching movement. Future studies may limit or constrain the reaching movement with more robust methods to detail finer movements in the MRE.

5.4.2 Maneuvering load in the MRE

The reach envelopes of all groups had a significant main effect of load, similar to reports in previous investigation of hand-held loads in the MRE (Johnston et al., 2016). A likely explanation for the difference due to load is the biomechanics of the shoulder joint and mechanisms for addressing load on a moment arm. Simply raising the arm in 90° of flexion or abduction increases the moment at the shoulder (Antony & Keir, 2010). Previous studies of holding a 1.0Kg, or 2.0Kg load while completing shoulder flexion or abduction movements increased the muscle activity of rotator cuff muscles by 20% of maximum contraction (Sigholm et al., 1983). Sigholm and colleagues (1983) reported that the smaller rotator cuff muscles were found to be more dependent on the hand-load interaction than the larger movers such as the deltoid. Sengputa and Das (1998) recorded muscular activity of the anterior deltoid, upper trapezius and erector spinae for normal, maximum and extreme reach. Moving into maximum reach, increased the muscle activity

of those three groups by 96, 37 and 48% respectively (Das & Sengputa, 1998). All of these findings support that small loads, especially requiring hand held loads have implications on the shoulder. Therefore, having a longer moment arm for the shoulder in maximum reach as opposed to normal reach, could explain one of the mechanisms through which reach is affected. Also the addition of load at the end of the moment arm impacts reach distance. Similarly, with the current research the moment arm would remain relatively the same throughout the load conditions, however the addition of a load may recruit more muscle activity to address the moment. Retraction of the scapula, or a flexion at the elbow may have been possible anatomical explanations for the reduction in the reach measure. Subjectively, trunk movement and elbow flexion were restricted however without completely stabilizing the subject or monitoring the kinematic data there is no definite answer as to what exactly occurred in the upper extremity to decrease reach.

An interesting finding was the lack of reach distance difference in the two load conditions. The 0.5Kg condition had a median reach of 535 mm, and the 1.0Kg condition had a median reach of 534 mm across participants. The difference of 0.5Kg between the two conditions there was the same as the 0.0 to 0.5 Kg effect but it had no significant difference in median reach. This raises the question of at what weight does a load condition begin to have an effect on the reach envelope. It also suggests investigation into at what additional increment might there be additional differences noticed. The odds of reaching into panels of the reach envelope were not greater without maneuvering a load in comparison to the two additional loads. Therefore, it is concluded that these small loads (0.5 Kg, 1.0 Kg) impact reach distance and slightly impact the overall area. The group by load by phi interaction found that the symptomatic group

Load had a significant effect on MRE reach distance for all participant groups. It also decreased the probability of reaching to a panel for all groups and therefore should be taken into consideration when understanding functional capability. People interact with small loads when performing reaching tasks in their workspaces (occupational or everyday activities). Therefore, regardless of injury, the factor of load should be taken into account in both ergonomic and clinical assessment measures as it is a measured factor affecting reach.

CHAPTER 6 CONCLUSIONS

This research study was completed to measure, quantify and compare the effects of shoulder impairment (rotator cuff tear), and small loads on the maximum each envelope. This research completed the following objectives:

1. Compared the use of two coordinate systems (cylindrical and spherical coordinates) in describing and representing the MRE;
2. Investigated the effectiveness of univariate and multivariate analyses in determining differences between and within the MRE of differing groups;
    i. Performed proof in principle analyses for methods to quantify the MRE.
3. Compared the effect of external loads on the maximum reach envelope of 3 subject groups: young asymptomatic, age-matched asymptomatic, and symptomatic (rotator-cuff tear).

6.1 Conclusions

Based upon the results of this research the following conclusions are made:

1. Converting three dimensional Cartesian coordinates into cylindrical coordinates is an applicable conversion for ergonomic applications due to its absolute cutoffs and relevance to design.
2. Converting the Cartesian coordinates into spherical coordinates is a more suitable conversion for clinical applications due to its relevance to current clinical assessment measurements.
3. Due to the complexity of the reach envelope data, it was necessary to use two main analyses for the MRE data. Analyzing the MRE by reach distance, and

by reach area was necessary to identify differences within and among the MRE.

4. Principal component analysis, while a useful tool in other human movement analyses, was not applicable for the structure and constraints of this dataset.
5. Development of predictive models of reach distance and area are possible with this type of data.
6. Normalization of the reach distance vector to arm length was a useful process to decrease individual variability and interpret group comparisons.
7. This was the first investigation to quantify the maximum reach envelope on a group of individuals with shoulder injuries (massive rotator cuff tears). There was a significant difference in the MRE (reach area) between the asymptomatic groups and the symptomatic group. There was no difference between the MRE (reach area) between age groups. In areas that were common between all groups, the younger asymptomatic group had a larger normalized reach distance than both the age-matched asymptomatic individuals and the symptomatic individuals.
8. With significant differences between the asymptomatic groups, it was concluded that a young adult population may not be the best normative data group for comparison to a symptomatic group with rotator cuff tears, in turn an age-similar asymptomatic group should be used.
9. Load had a significant effect on MRE reach distance for all participant groups. It also decreased the probability of reaching to a panel for all groups.

6.2 Future Considerations

There are applications of this research in both ergonomics and health research. Moving forward, it will be imperative to understand the target audience of the MRE outcome measures. One consumer of this information is the measurement and evaluation science cohort, where the MRE measurements could be used in future ergonomic design. Having the MRE measurement of an injured population is important for design purposes in terms of prevention and intervention for upper extremity injuries, specifically rotator cuff tears. Ergonomic literature can utilize these dimensions in order to prevent the occurrence of shoulder injury in reaching tasks, and create accommodating designs for those living with injury. The clinical applications of this research are at a foundation stage. The MRE is a quantifiable measure for persons with rotator cuff tears. Future goals of this research area include the development of a comprehensive functional reach measurement tool that aids in clinical assessment of the shoulder. Dissemination of the MRE metric will require a large collaborative team to transfer the knowledge gained in the measurement phase into current practice.

1. Further investigation into the dependence of paneled areas of the MRE should be performed. Pure statistical inference to the paneling of MRE data, regardless of the coordinate system will better improve collection feasibility, and comparison between groups.
2. Relating the spherical data outputs of the MRE to current clinical standards could be achieved with this dataset, however, this could be a validation of the MRE to current clinical standards.
3. Principal component analysis or other pattern recognition analyses should be revisited with updated changes in the underlying collection methodology.

4. Clinical applications of this measure will benefit from understanding the tradeoff between reach distance and reach area in the MRE.
5. Measurement of the MRE in conjunction with compensatory mechanisms could better quantify the functional capability of the shoulder.

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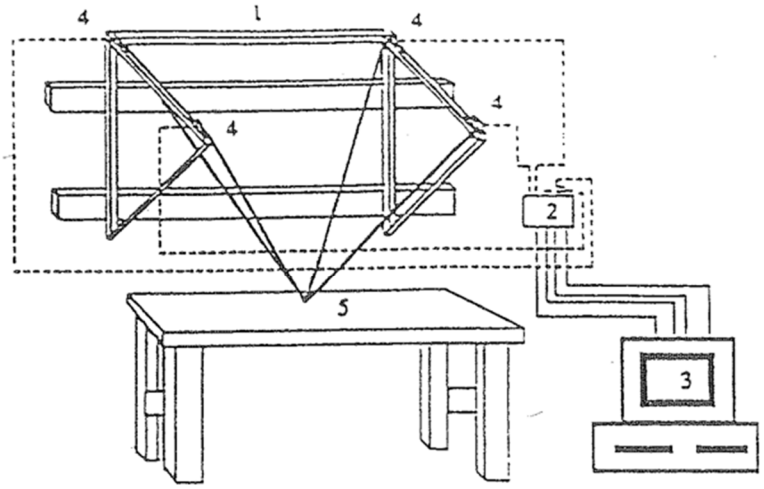
APPENDIX A



Legend:

1. Support frame
2. Potentiometer power supply
3. Digital computer with A/D converter
4. Location of the PRUs
5. Moveable pointer

Detailed schematic of the pointer:

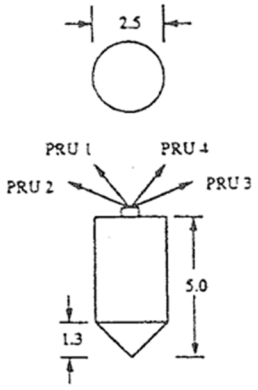


Figure 2. Schematic diagram of the computerized potentiometric system. All dimensions are given in cm.

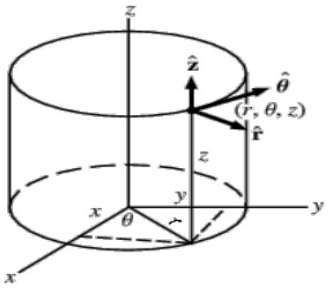
A computerized potentiometric system for structural and anthropometric measures. CPSAM Figure retrieved from (Kozey, Das, & Tyson, 1994).

APPENDIX B

Modeling Approaches to the Maximum Reach Envelope

Cylindrical Coordinates:

The application of a cylinder to modeling the reach envelope, creates reach distance vectors in the form of *(r, θ, Z)*. In paneling the reach envelope, levels of Z correspond to the incremental heights in millimeters above or below acromial height. The angular regions are created using θ, and are divided by 30 degree increments where 0 degrees is created by the frontal midline axis.



Conversion from cylindrical to cartesian (rectangular):

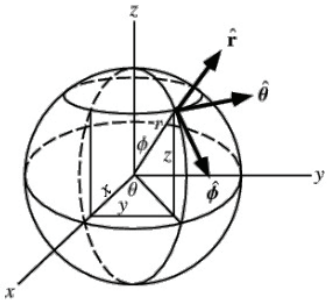
$$x = r\cos\theta \qquad y = r\sin\theta$$
$$z = z$$

Conversion from cartesian to cylindrical:

$$r = \sqrt{x^2 + y^2}$$
$$\cos\theta = \frac{x}{r} \quad \sin\theta = \frac{y}{r} \quad \tan\theta = \frac{y}{x}$$
$$z = z$$

Spherical Coordinates:

A spherical model has been used as an alternate approach to modelling the reach envelope. Kozey and Mackenzie (2002) highlighted that the spherical approach performed better at modelling reach within the midsection, but decreased in accuracy in the periphery. The panelled sections of the reach envelope are created by angular divisions *(θ, ϕ)* about the horizontal and vertical axes with an origin at the acromion.



Note: In this picture, r should be ρ.

Conversion from spherical to cartesian (rectangular):

$$x = \rho\sin\varphi\cos\theta$$
$$y = \rho\sin\varphi\sin\theta$$
$$z = \rho\cos\varphi$$

Conversion from cartesian to spherical:

$$r = \sqrt{x^2 + y^2} \qquad \rho = \sqrt{x^2 + y^2 + z^2}$$
$$\cos\theta = \frac{x}{r} \quad \sin\theta = \frac{y}{r} \quad \tan\theta = \frac{y}{x}$$
$$\cos\varphi = \frac{z}{\rho}$$

Figures retrieved from: https://www.slideshare.net/leingang/lesson-6-polar-cylindrical-and-spherical-coordinates

APPENDIX C

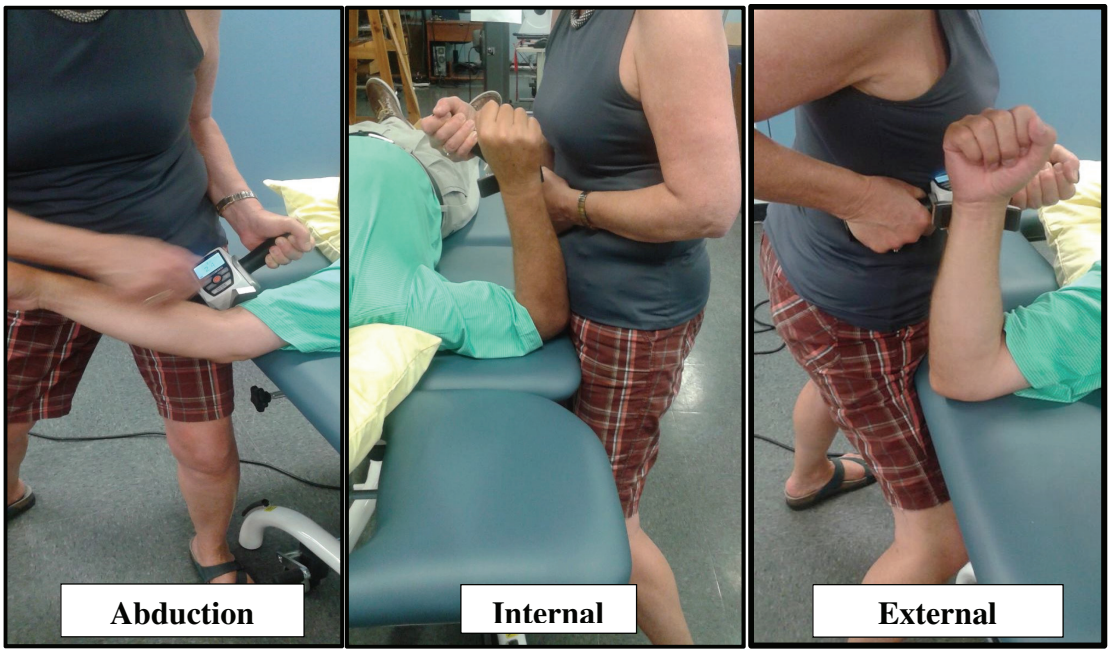
CPSAM Reach Study Clinical Measures July 2016

Strength Measures

- Measures to be completed in **supine**
- Dynamometer set up : curved pad contact + dual-end handle
- Measure in Kg of Force for the clinical assessment form

Strength: Abduction, Internal, External Rotation

- □ Supine position, arm fully extended 90 degrees
- □ Palpate bony landmarks and mark:
  - Acromion
  - Lateral epicondyle
- □ Locate point of application (superior to elbow); mark
- □ Locate point of application anterior and posterior (wrist); mark
- □ Measure in mm
  - Distance from acromion > point of appl. Near elbow
  - Distance from point of application on wrist > lateral epicondyle



APPENDIX C

Range of Motion Meaures

- Active Measures to be completed in standing, passive in supine
- Centre of goniometer at centre of rotation
- Complete active ROM measures first (especially with clinical population to see comfortable limits)

ACTIVE

Flexion

- Standing bilateral forward flexion, maintaining movement at the shoulder joint, watch for thoracic extension
- Goniometers arms along scapular line (side of body) and trace 2nd arm along line of upper arm through elbow

Abduction

- Standing, bilateral lateral elevation (abduction) out to the sides of the subject

External and Internal Rotation

- Series of checkboxes as outlined by the Assessment Form, no numerical measurements

PASSIVE

- Measures similar to active, bring subject through full ROM, measure in supine, record trials in degrees

SPINE MEASURE USING FLEXIRULER

- Mark C7, L5-S1 junction
- Press ruler into subject's spine, remove and trace *Right Side* on flow chart paper.
- Measurements according to handouts.

APPENDIX D

Testing assumptions for general linear models

General linear models (GLM) were used in the analysis to assess differences in reach distances, normalized reach distances and to create prediction models. There were select assumptions required to perform these GLMs. For basic analysis of variance models (ANOVA) independent sample groups, normality, and homogeneity of variance are required. With respect to the models created in this study there were multiple factor levels. The factors of injury group (young asymptomatic, age-matched asymptomatic, and symptomatic), and load (0, 0.5, 1.0 Kg) were some of the noted main effects tested. These main effects were independent from one another. The assumption of normality was included for its influence on parametric tests and performed using Kolmogorov-Smirnov statistics and interpretation of Q-Q normality plots. Figure 1 displays the normality plot and associated KS statistic, display non-normal data. However, central limit theorem states that any data set with number of samples greater than 30, the distribution of sample means is fairly normally distributed. This data set was not quite a sample of 30 (and each sample group was 10, 10 and 6 participants large). Yet with a large number of observation the QQ plot displays how the data is fairly normally distributed with tails (very large and very small observations) affecting the normality test. Through further investigation it was determined that any GLM is fairly robust to these

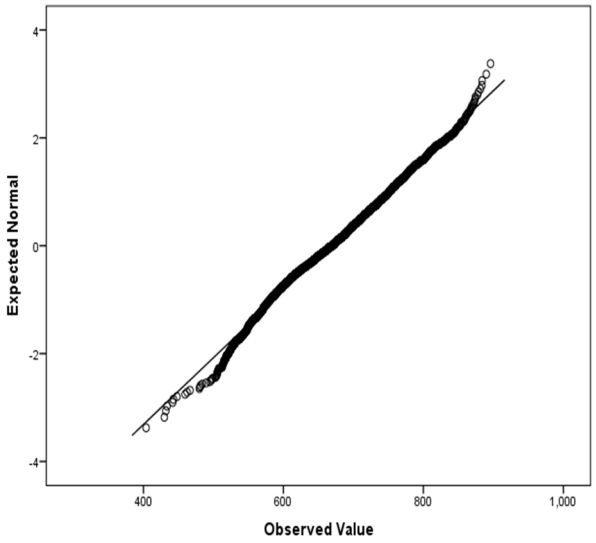


Figure 1 Q-Q plot of median reach distance for all groups; data not normally distributed KS (2719) =.036, p<.001.

small outliers, and that the dependent variable need not be necessarily be normally distributed (McCullagh & Nelder 1989).

Upon completing the general linear model for the normalized reach data the residuals were plotted using Minitab Statistical Software. Figure 2 displays the normal probability plot and histogram along with the fitted values and observations. Aside from an outlier with a large residual of -0.4, the errors were normally distributed.

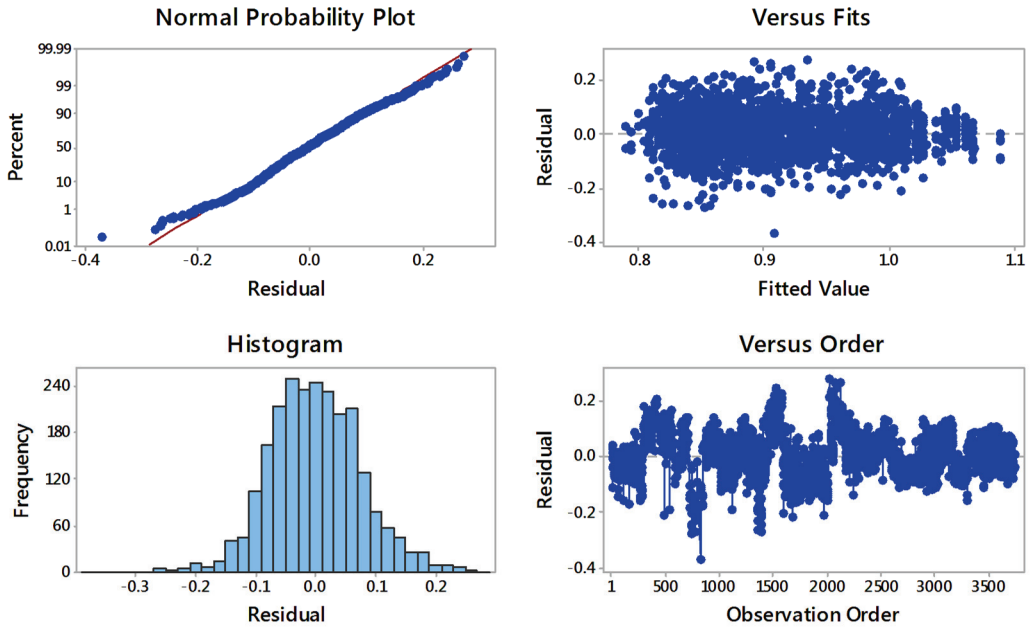


Figure 2. Fits and normality of the errors of the GLM model fitted for the normalized reach distance for all group and load conditions.

APPENDIX E

Principal Component Analysis on a Pilot Data Set

A principal component extraction method was used to determine the independent components of a small 10 participant dataset. For a complete PCA to be computed, there are a variety of assumptions that must be met. The size of the data set is one overall assumption that influences other assumptions of sphericity and multicollinearity. This dataset was too small for full analysis or to compute factor loadings, however pattern recognition will be discussed. Four principal components (PCs) were chosen as they accounted for 93.8 % of the total variance of the entire data set. Three main components were retained on this small pilot data set: PC1 mid theta region, PC2 across body theta region, and PC3 highest Z level. The table below highlights where variables (panels of the reach envelope) held highly correlated factor loadings for each of the PCs. PCA on the young asymptomatic dataset:

Table 2. Rotated Component Matrix for paneled reach data

	Component			
	1	2	3	4
VAR00004	.097	-.352	.740	-.169
VAR00005	.645	.105	-.329	.667
VAR00006	.931	-.207	-.119	.206
VAR00007	.932	-.113	-.118	.169
VAR00008	.865	.151	-.370	.198
VAR00009	.647	.520	-.408	.229
VAR00010	.060	.800	.116	.432
VAR00011	.157	.744	-.380	.505
VAR00012	.681	.573	-.390	.170
VAR00013	.824	.495	-.113	-.005
VAR00014	.757	.507	-.282	.225
VAR00015	.121	.950	-.150	.056
VAR00016	.495	.657	.204	.509
VAR00017	.645	.724	-.039	.131
VAR00018	.786	.532	-.256	.150
VAR00019	.868	.404	.031	-.090
VAR00020	.810	.513	-.267	.083
VAR00021	.245	.941	-.130	-.042
VAR00022	.402	.541	.612	.242
VAR00023	.577	.544	-.026	.511
VAR00024	.846	.410	.028	.282
VAR00025	.903	.390	.133	.009
VAR00026	.861	.479	-.065	.111
VAR00027	.377	.912	-.005	-.051
VAR00028	.581	.116	.633	.265
VAR00029	.584	.689	.118	.148
VAR00030	.709	.497	.264	.360
VAR00031	.845	.405	.311	-.021
VAR00032	.857	.478	.143	.082
VAR00033	.554	.766	.195	-.140
VAR00034	-.545	-.371	.727	.042
VAR00035	-.687	-.355	.624	.048
VAR00036	-.348	-.033	.904	.027
VAR00037	.096	.249	.911	-.020
VAR00038	-.029	.102	.967	-.162
VAR00039	-.546	-.424	.646	.048

Extraction Method: Principal Component Analysis.
Rotation Method: Varimax with Kaiser Normalization.

PCA is an orthogonal data decomposition technique. In mathematical terms, PCA transforms correlated variables from the data into smaller uncorrelated and independent variables called components. It is common in the biomechanical and ergonomics literature with pattern recognition and feature detection (Astephen & Deluzio, 2007).

In order to assess if PCA could work as an analysis, the 10 young asymptomatic group data was used as a trial. The paneled data for each participant and the 0 Kg load condition were entered into SPSS statistical software as row data. Columns containing the 54 panels of the median reach distance in the MRE were used as the main variables for analysis. It should be noted that PCA requires large amounts of data, however these 10 participants had the most reached panels of all 3 participant groups and therefore the least amount of "missing data". The data violated the few assumptions regarding factor analysis, and extraction. Bartlett's test of sphericity and the Kaiser Meyen Olkin measure of sampling adequacy were violated, as there was not enough data from participants. A proof in principle interpretation of the data was made ignoring this, in order to further investigate the use of PCA.

A principal component extraction method was used to determine the independent components of the data. Table 1 in Appendix E displays the factor loadings for the four chosen factors of the PCA. These four factors were chosen as they accounted for 93.8 % of the total variance of the data set and all had an eigenvalue greater than 1. With respect to the paneled reach data these variables represent areas of the reach envelope in thetas 3, 4, and 5. These angular positions represent just to the right and in front of a participant's acromion. The second component had high factor loadings with the last thetas 7, 8, 9 as indicated in Figure 2. These are the farthest distance a person would reach across their

body to create the MRE. Finally, component 3 had high factor loadings across the last 6 variables, which were all thetas in the highest height division of greater than 500 mm above acromial level.

While there were some characteristic patterns that might be understood through PCA, there were multiple violations that made this test difficult on an asymptomatic group. In combing this analysis with the symptomatic group, where there was much of the MRE with no recorded data, the PCA would be unable to account for the areas the participants could not reach. Therefore, it was not determined to be the best current method for analysis.

The small investigation of PCA on the young asymptomatic group served as a starting point for the use of PCA in reach envelope measurement and quantification. Three main components were retained on this small pilot data set: PC1 mid theta region, PC2 across body theta region, and PC3 highest Z level. These areas accounted for a large amount of variance within the data set. Visually examining the median reach distances across the panels of the reach envelopes agrees with these PCs. With 3 main categories representing the overall reach envelope in this proof of principle analysis, these areas may be combined in future analyses to investigate alternative methods in paneling the data.

The benefit of adding the PCA is the ability to detect pattern differences. Using the different areas of the reach envelope (the different PCs), it becomes clearer where participants or sub groups may differ in reach. It will be useful to see how different population sub groups present in a PCA analysis. While other kinematic measures such as gait, truly benefit from the use of this technique, the current methodology does create interpretable data through PCA (Astephen & Deluzio, 2007). The next step with this

MRE research is to create a comprehensive functional reach test that can be used pre and post rotator cuff surgery to describe shoulder function. With a revised methodology, i.e. allowing participants to perform elbow flexion, PCA may be used break down areas of the reach envelope that best describe functional reach, therefore making individual comparison easier in the recovery stage of rehabilitation.

APPENDIX F

Appendix E contains all documents completed in collaboration with the research assistants from Nova Scotia Health Authority. The following documents from this department are listed:

1) Research Ethics Board Human Ethics Approval (page 100)
2) Clinical Examination Record Sheet, document used to record range of motion and strength measures (page 101)
3) Asymptomatic consent form (page 103)
4) Symptomatic consent form (page 112)

1) REB Ethics Approval –through Nova Scotia Health Authority

Nova Scotia Health Authority Research Ethics Board
Centre for Clinical Research, Room 118
5790 University Avenue
Halifax, Nova Scotia, Canada B3H 1V7
joan.morrison@nshealth.ca

February 02, 2017

Dr. Ivan Wong
Medicine\Surgery\Orthopedic Surgery
5955 Veterans' Memorial Lane
Room 2106, VMB
Halifax, NS
B3H 2E1

Dear Dr. Wong:

RE: Using a Computerized Potentiometric System for Anthropometric Measures (CPSAM) to Obtain Maximum Reach Envelope in Individuals with Full Thickness Rotator Cuff Tears - A Pilot Study

NSHA REB ROMEO FILE #: 1019986

On behalf of the Nova Scotia Health Authority Research Ethics Board (NSHA REB) I have examined the proposed amendment to this research study. I am pleased to confirm the Board's approval of this amendment request, effective February 02, 2017.

The following denotes new items approved with this amendment:

Document Name	Comments	Version Date
FYI Letter/Update to the Board	Cover Letter with details on Amendments	2017/01/12
Research Protocol	Revised Protocol	2017/01/12
Consent Form	Consent_Asymptomatic - Version 3	2017/01/25

Sincerely,

Dr. Chris MacKnight, Executive Chair

This statement is in lieu of Health Canada's Research Ethics Board Attestation:
The Research Ethics Board for the Nova Scotia Health Authority operates in accordance with:
- Food and Drug Regulations, Division 5 "Drugs for Clinical Trials Involving Human Subjects"
- Natural Health Products Regulations, Part 4 "Clinical Trials Involving Human Subjects"
- Tri-Council Policy Statement: Ethical Conduct for Research Involving Humans (TCPS 2)
- ICH Good Clinical Practice: Consolidated Guideline (ICH-E6)

2) Clinical Assessment form used to collect range of motion and strength measures.

Follow-Up Clinical Exam

Subject ID: ☐☐☐☐☐☐☐☐☐☐

☐ Evaluation was not done	Form Completion Date: Y Y M M D D	
1. Surgical Site Healing Assessment Comments	2. Swelling Assessment (check one box only)	
☐ a.	☐ a. No swelling	
	☐ b. Localized swelling around suture line	
☐ b.	☐ c. Generalized wound swelling	
	☐ d. Fluctuating swelling	
3. Evidence of Infection	☐ Yes	☐ No
4. Has the subject returned to work?		
☐ Yes →	Date returned Y Y M M D D	☐ Date returned to work was previously reported at an earlier visit
☐ No →	Is return to work delayed due to their operative shoulder?	☐ Yes
		☐ No

Study Outcomes:

STRENGTH (pounds) ☐ 3 month ☐ 6 month ☐ 12 month ☐ 24 month ☐ Not done

Abduction		External Rotation		Subscap	
☐ 0	☐ 13-15	☐ 0	☐ 13-15	☐ 0	☐ 13-15
☐ 1-3	☐ 15-18	☐ 1-3	☐ 15-18	☐ 1-3	☐ 15-18
☐ 4-6	☐ 19-21	☐ 4-6	☐ 19-21	☐ 4-6	☐ 19-21
☐ 7-9	☐ 22-24	☐ 7-9	☐ 22-24	☐ 7-9	☐ 22-24
☐ 10-12	☐ >24	☐ 10-12	☐ >24	☐ 10-12	☐ >24

ACTIVE RANGE OF MOTION ☐ 3 month ☐ 6 month ☐ 12 month ☐ 24 month ☐ Not done

Forward Flexion	Lateral Elevation	External Rotation	Internal Rotation
☐ 61-90	☐ 61-90	☐ Hand behind Head, Elbow forward	☐ Buttock
☐ 91-120	☐ 91-120	☐ Hand behind Head, Elbow back	☐ Lumbosacral Junction
☐ 121-150	☐ 121-150	☐ Hand to top of Head, Elbow forward	☐ Waist (L3)
☐ 151-180	☐ 151-180	☐ Hand to top of Head, Elbow back	☐ T12 Vertebra
		☐ Full Elevation from top of Head	☐ Interscapular (T7)

PASSIVE RANGE OF MOTION ☐ 6 week ☐ 3 month ☐ 6 month ☐ 12 month ☐ 24 month	
Forward Flexion	°
Abduction	°
External Rotation	°
Internal Rotation	°

Version 3 – September 3rd , 2015

Informed Consent Form

STUDY TITLE:	***Using a Computerized Potentiometric System for Anthropometric Measures (CPSAM) to Obtain Maximum Reach Envelope in Individuals with Full Thickness Rotator Cuff Tears - A Pilot Study***
PRINCIPAL INVESTIGATOR:	***Dr Ivan Wong MD, FRCS(C), Dip. Sports Med., MACM*** *5655 Veteran's Memorial Lane,* *Camphill Veterans Memorial Building, Room 2106.* *Halifax, NS B3H 2E1*
FUNDER:	Funding for this study is pending from the Nova Scotia Health Research Foundation

1. Introduction

You have been invited to take part in a research study. A research study is a way of gathering information on a treatment, procedure or medical device or to answer a question about something that is not well understood. Taking part in this study is voluntary. It is up to you to decide whether to be in the study or not. Before you decide, you need to understand what the study is for, what risks you might take and what benefits you might receive. This consent form explains the study.
Please ask the research team to clarify anything you do not understand or would like to know more about. Make sure all your questions are answered to your satisfaction before deciding whether to participate in this research study.

The researchers will:

- Discuss the study with you
- Answer your questions
- Be available during the study to deal with problems and answer questions

You are being asked to consider participating in this study because you are a patient of Dr. Ivan Wong's that has previously had an MRI, which shows you have a full thickness/massive tear in your rotator cuff and have not yet had it repaired surgically. If you decide not to take part or if you leave the study early, your usual health care will not be affected.

1.2 Why Am I Being Asked To Join This Study?

You are being asked to join this study because you fit in one of the study groups:

Group without rotator cuff tear: This group has no symptoms of shoulder injury, but each one of the participants will be approximately the same age, and sex as one of the

people in our symptomatic rotator cuff injured group. Thus, you make up a “control” group.

2. Why Is This Study Being Conducted?

The purpose of this study is to examine the accuracy of CPSAM (computerized potentiometric system for anthropometric measures) to assess maximum reach envelopes (which is the largest circle coordinates that your injured arm can reach) in individuals with massive rotator cuff tears (RCTs). The low cost, accuracy and ease of use with CPSAM makes it a suitable measurement system to consider it for clinical application in determining the full range of motion of individuals with shoulder impairments potentially requiring operative intervention.

Osteoarthritis (OA) is known to develop after a rotator cuff tear. OA in the shoulder has been noted to be the third most affected joint resulting in surgery in the US, after the hip and knee. The limited function that results is more significant, as a high number of daily regular activities relies on shoulder function. As a result, it is important to continually monitor function of upper extremity such as the shoulder, as a method to reduce health care dollars and individual disability. With the continuing advancement of surgical procedures, there still remains an large challenge to demonstrate these procedures are effective in helping patients to obtain an improved and optimal state of function.

The goals post treatment are to decrease the pain that the patient feels and increase shoulder function. This requires an accurate assessment of the functional capabilities of the individual, which includes range of motion and strength. There are already known methods for testing these, but it is hoped that this study can focus on obtaining maximum reach envelope for individuals with massive RCT’s and be used to further assess function on an individual basis.

3. How Long Will I Be In The Study?

The length of this study for participants is 2 hours. The entire study is expected to take about four to six months to complete recruitment and data collection of all participants in this study and the results should be known in 1 year.

4. How Many People Will Take Part In This Study?

It is anticipated that a total of 40 people will participate in this study at the Queen Elizabeth Health Sciences Center and Dalhousie University.

5&6. How Is The Study Being Done & What Will Happen If I Take Part In This Study?

There are two parts to the research study.

1. Your routine clinic appointment with Dr. Ivan Wong:

If you agree to take part in this study and informed consent is obtained, you will fill out brief baseline questions, as well as, the VR-12, DASH and WORC questionnaires. These questionnaires are anticipated to take approximately 10-15 minutes for you to complete and are relating to your levels of experienced pain, perceived function and functional deficits related to your health and well being due to your rotator cuff tear injury. You will also complete a range of motion (ROM) test of the affected shoulder in flexion, extension, abduction, adduction, internal and external rotation, using a standard goniometer, in order to obtain the complete range of motion. You will also be asked to complete a strength test with a Dynamometer. These two strength and ROM tests together will take approximately 15 minutes to complete.

2. Your Active participation at the Biomechanics Lab at Dalhousie University:

Following your clinic appointment with Dr. Ivan Wong (PI), you will either head over to Dalhousie if timing permits or you can choose when would be an appropriate time for you to head over to Dalhousie for measurements tests with the CPSAM. If you choose to wait to decide on an appropriate time for you to head to the Dalhousie Biomechanics Lab, you will be contacted by one of the members of the research team 3 days after your clinic appointment to schedule your testing of your maximum reach envelope.

Once you are at the Biomechanics Laboratory, you will then meet with one of the members of the research team and be asked to perform various movements of the affected shoulder. Following this, you will then have your maximum reach envelope mapped using our computerized system, which will interpret your movements while you hold a pointer with your affected hand and perform a series of horizontal sweep movements from as far left as you can reach through to the right side. Next, you will raise your hand approximately 5 cm and continue the motion in the opposite direction. These movements will continue until you have reached your maximum reach envelope. Each trial will be collected for a total of 45 seconds

You will perform a total of 18 trials of maximum-seated reach. You will sit either front or side facing under 3 different conditions – with no-load, 0.5 or 1.0 Kg load, with three different trials of each. The zero load condition will take place first, followed by random

integration of the other two conditions. You will have two practice trials before any data is collected.

You will have 2-3 minutes rest in between trials if you desire. If at any point in time you feel as though you are unable to complete any of the activities involved in the research study, or do not want to take part, you are free to choose not to participate in any further testing for the study.

The duration of time predicted to be spent for participants in the lab is one hour. There are no subsequent visits expected of participants to the lab or to clinic at the QEII for the purposes of this research project.

3. Photography and Video-Photography

Photography and video-photography will be collected during this experiment. The primary purpose of the video and any photographs is to use them as a visual reference to compare with the measured reach from the measurement instrument to the video image and for educational purposes. In order to participate in this study, you will need to consent to the taking of photo and video records. You will have the opportunity to refuse the use of photographs or video footage for the purposes of reporting and presentations. You will also have the option to consent to the use of photographic or video imagery for the above stated purposes provided your identity is masked.

7. Are There Risks To The Study?

Breach of confidentiality: As with all research, there is a chance that confidentiality could be compromised; however, we are taking precautions to minimize this risk. Such precautions include de-identifying patient information with a code number and keeping study data in a locked cabinet.

Questionnaires: You may find the interviews and questionnaires you receive during the course of the study upsetting or distressing. You may not like all of the questions that you will be asked. You do not have to answer those questions you find too distressing.

Performing range of motion and reach envelope in the lab: You may find that you encounter pain or discomfort while performing these movements. You may take as much rest as you need during this portion of the study and/or in between trials (on top of the 2-3 minutes mentioned earlier), or if you feel you are unable to complete the necessary activities you can withdraw your participation.

8. Are There Benefits Of Participating In This Study?

You will not receive any direct medical benefits from participating in this research. You may help future patients with the rotator cuff injury and other potential shoulder injuries by helping collect data to develop an efficient low cost outcome measurement tool.

9. What Happens at the End of the Study?

It is anticipated that the results of this study will be published and or presented in a variety of forums. In any publication and/or presentation, information will be provided in such a way that you cannot be identified, except with your express permission.

10. What Are My Responsibilities?

As a study participant you will be expected to:

- Follow the directions of the research team;
- Report any changes in your health to the research team;
- Report any problems that you experience that you think might be related to participating in the study;

11. Can My Participation in this Study End Early?

Yes. If you chose to participate and later change your mind, you can say no and stop the research at any time. If you wish to withdraw your consent please inform the research team. If you choose to withdraw from this study, your decision will have no effect on your current or future medical treatment and healthcare. Withdrawal of study participation can include withdrawal of personal data collected up until that point. Also, data collected up until that point will not be included in the study analyses.

Lastly, the principal investigator may decide to remove you from this study without your consent for any of the following reasons*:*

- You do not follow the directions of the research team;
- You are experiencing high levels of pain or discomfort throughout your participation in the study, affecting your ability to perform the necessary movements required by the researchers

If you are withdrawn from this study, one of the members of the research team will discuss the reasons with you and plans will be made for your continued care outside of the study.

13. What About New Information?

You will be told about any other new information that might affect your health, welfare, or willingness to stay in the study and will be asked whether you wish to continue taking part in the study or not.

14. Will It Cost Me Anything?

Participating in this study will not involve any additional costs to you. You may be reimbursed for some study related expenses such as parking at the Dalhousie Occupational Biomechanics and Ergonomics laboratory. Please bring your receipts with you. You will receive payment at each visit throughout the study. If you decide to leave the study, you will receive a prorated payment for participating in the study.

Research Related Injury

If you become ill or injured as a direct result of participating in this study, necessary medical treatment will be available at no additional cost to you. Your signature on this form only indicates that you have understood to your satisfaction the information regarding your participation in the study and agree to participate as a subject. In no way does this waive your legal rights nor release the principal investigator, the research staff, the study sponsor or involved institutions from their legal and professional responsibilities.

15. What About My Privacy and Confidentiality?

Protecting your privacy is an important part of this study. Every effort to protect your privacy will be made. If the results of this study are presented to the public, nobody will be able to tell that you were in the study. However, complete privacy cannot be guaranteed. For example, the investigator may be required by law to allow access to research records.

If you decide to participate in this study, the research team will look at your personal health information and collect only the information they need for this study. "Personal health information" is health information about you that could identify you because it includes information such as your;

- Name
- Age
- Gender
- Date of Injury
- Dominant Hand
- Height
- Weight

This personal health information will be used in the most de-identified manner by the research team and will solely be used for the purposes of patient characteristic calculations, as well as, better understanding the results presented in the specific patient populations.

Access to Records

Other people, during visits to this health care facility, may need to look at your personal health information to check that the information collected for the study is correct and to make sure the study followed the required laws and guidelines. These people include the Nova Scotia Health Authority Research Ethics Board (NSHA REB) and people working for or with the NSHA REB because they oversee the ethical conduct of research studies at Nova Scotia Health Authority. The REB and people working for or with the REB may also contact you personally for quality assurance purposes.

Use of Your Study Information

Any study data about you that is sent outside of Nova Scotia Health Authority will have a code and will not contain your name or any information that directly identifies you. The data that is sent outside of Nova Scotia Health Authority will be used for the research purposes explained in this consent form.

The research team and the NSHA Research Ethics Board will keep the information they see or receive about you confidential, to the extent permitted by applicable laws. Even though the risk of identifying you from the study data is very small, it can never be completely eliminated.

The research team will keep any personal information about you in a secure and confidential location for 7 years and then destroy it according to Nova Scotia Health Authority policy. Your personal health information will not be shared with others. After your part in the study ends, your regular clinical care with Dr. Ivan Wong will continue as routine.

Your Access to Records

You have the right to access, review, and request changes to your study data.

16. Declaration of Financial Interest

The amount of payment is sufficient to cover the costs of conducting the study. The principal investigator and co-investigators have no vested financial interest in conducting this study.

17. What About Questions or Problems?

For further information about the study you may call the principal investigator, who is the person in charge of this study and/or any other research team member listed below.

Principal Investigator:
Dr. Ivan Wong

Telephone: (902) 473-7626

Co-Investigators:
Dr. John Kozey, telephone: (902) 494-1148

The Research Assistant:
Heather Johnston (613) 207-0741
Colleen Dewis (902) 494-2066
Nicole Paquet (902) 473-7626

18. What Are My Rights?

You have the right to all information that could help you make a decision about participating in this study. You also have the right to ask questions about this study and your rights as a research participant, and to have them answered to your satisfaction before you make any decision. You also have the right to ask questions and to receive answers throughout this study.

If you have any questions about your rights as a research participant, contact Patient Relations at (902) 473-2133 or healthcareexperience@nshealth.ca. If you are calling us long distance (NS, NB and PEI), please use our toll free number 1-855-799-0990.

In the next part you will be asked if you agree (consent) to join this study. If the answer is "yes", please sign the form.

19. Consent Form Signature Page

I have reviewed all of the information in this consent form related to the study called: **Using a Computerized Potentiometric System for Anthropometric Measures (CPSAM) to Obtain Maximum Reach Envelope in Individuals with Full Thickness Rotator Cuff Tears - A Pilot Study.**

I have been given the opportunity to discuss this study. All of my questions have been answered to my satisfaction. This signature on this consent form means that I agree to take part in this study. I understand that I am free to withdraw at any time without affecting my future care.

I understand that all experimental trials will be video recorded for validation purposes. I have been informed that I am required to make a decision regarding the usage of the video and photographic material that is recorded during the completion of this research.

I voluntarily consent to video footage and photography being taken throughout the experiment for data analysis purposes.

Regarding the use of these images, please circle the appropriate response to which you agree. You have the ability to change this decision regarding the use of video or photographic material until 2 weeks after the completion of data collection.

The research team is free to use video or photographic records that include me for the purposes of knowledge translation, presentations, or publications. My identity will be masked. _____ (Initials)	No video or photographic material containing me may be used for any purpose other than data analysis. _____(Initials)

_____	_____	____ / _____ / ____
Signature of Participant	Name (Printed)	Year Month Day*
_____	_____	____ / _____ / ____
Signature of Person Conducting Consent Discussion	Name (Printed)	Year Month Day*
_____	_____	____ / _____ / ____
Signature of Investigator	Name (Printed)	Year Month Day*

Informed Consent Form

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PRINCIPAL INVESTIGATOR:	***Dr Ivan Wong MD, FRCS(C), Dip. Sports Med., MACM*** *5655 Veteran's Memorial Lane,* *Camphill Veterans Memorial Building, Room 2106.* *Halifax, NS B3H 2E1*
FUNDER:	Funding for this study is pending from the Nova Scotia Health Research Foundation

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integration of the other two conditions. You will have two practice trials before any data is collected.

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The duration of time predicted to be spent for participants in the lab is one hour. There are no subsequent visits expected of participants to the lab or to clinic at the QEII for the purposes of this research project.

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Performing range of motion and reach envelope in the lab: You may find that you encounter pain or discomfort while performing these movements. You may take as much rest as you need during this portion of the study and/or in between trials (on top of the 2-3 minutes mentioned earlier), or if you feel you are unable to complete the necessary activities you can withdraw your participation.

8. Are There Benefits Of Participating In This Study?

You will not receive any direct medical benefits from participating in this research. You may help future patients with the rotator cuff injury and other potential shoulder injuries by helping collect data to develop an efficient low cost outcome measurement tool.

9. What Happens at the End of the Study?

It is anticipated that the results of this study will be published and or presented in a variety of forums. In any publication and/or presentation, information will be provided in such a way that you cannot be identified, except with your express permission. At the end of your participation in the study, your regular healthcare will continue with Dr. Ivan Wong as planned

10. What Are My Responsibilities?

As a study participant you will be expected to:

- Follow the directions of the research team;
- Report any changes in your health to the research team;
- Report any problems that you experience that you think might be related to participating in the study;

11. Can My Participation in this Study End Early?

Yes. If you chose to participate and later change your mind, you can say no and stop the research at any time. If you wish to withdraw your consent please inform the research team. If you choose to withdraw from this study, your decision will have no effect on your current or future medical treatment and healthcare. Withdrawal of study participation can include withdrawal of personal data collected up until that point. Also, data collected up until that point will not be included in the study analyses.

Lastly, the principal investigator may decide to remove you from this study without your consent for any of the following reasons*:*

- You do not follow the directions of the research team;
- You are experiencing high levels of pain or discomfort throughout your participation in the study, affecting your ability to perform the necessary movements required by the researchers

If you are withdrawn from this study, one of the members of the research team will discuss the reasons with you and plans will be made for your continued care outside of the study.

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You will be told about any other new information that might affect your health, welfare, or willingness to stay in the study and will be asked whether you wish to continue taking part in the study or not.

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Participating in this study will not involve any additional costs to you. You may be reimbursed for some study related expenses such as parking at the Dalhousie Occupational Biomechanics and Ergonomics laboratory. Please bring your receipts with you. You will receive payment at each visit throughout the study. If you decide to leave the study, you will receive a prorated payment for participating in the study.

Research Related Injury

If you become ill or injured as a direct result of participating in this study, necessary medical treatment will be available at no additional cost to you. Your signature on this form only indicates that you have understood to your satisfaction the information regarding your participation in the study and agree to participate as a subject. In no way does this waive your legal rights nor release the principal investigator, the research staff, the study sponsor or involved institutions from their legal and professional responsibilities.

15. What About My Privacy and Confidentiality?

Protecting your privacy is an important part of this study. Every effort to protect your privacy will be made. If the results of this study are presented to the public, nobody will be able to tell that you were in the study. However, complete privacy cannot be guaranteed. For example, the investigator may be required by law to allow access to research records.

If you decide to participate in this study, the research team will look at your personal health information and collect only the information they need for this study. "Personal health information" is health information about you that could identify you because it includes information such as your;

- Name
- Age
- Gender
- Date of Injury
- Dominant Hand
- Height
- Weight

This personal health information will be used in the most de-identified manner by the research team and will solely be used for the purposes of patient characteristic calculations, as well as, better understanding the results presented in the specific patient populations.

Access to Records

Other people, during visits to this health care facility, may need to look at your personal health information to check that the information collected for the study is correct and to make sure the study followed the required laws and guidelines. These people include the Nova Scotia Health Authority Research Ethics Board (NSHA REB) and people working for or with the NSHA REB because they oversee the ethical conduct of research studies at Nova Scotia Health Authority. The REB and people working for or with the REB may also contact you personally for quality assurance purposes.

Use of Your Study Information

Any study data about you that is sent outside of Nova Scotia Health Authority will have a code and will not contain your name or any information that directly identifies you. The data that is sent outside of Nova Scotia Health Authority will be used for the research purposes explained in this consent form.

The research team and the NSHA Research Ethics Board will keep the information they see or receive about you confidential, to the extent permitted by applicable laws. Even though the risk of identifying you from the study data is very small, it can never be completely eliminated.

The research team will keep any personal information about you in a secure and confidential location for 7 years and then destroy it according to Nova Scotia Health Authority policy. Your personal health information will not be shared with others. After your part in the study ends, your regular clinical care with Dr. Ivan Wong will continue as routine.

Your Access to Records

You have the right to access, review, and request changes to your study data.

16. Declaration of Financial Interest

The amount of payment is sufficient to cover the costs of conducting the study. The principal investigator and co-investigators have no vested financial interest in conducting this study.

17. What About Questions or Problems?

For further information about the study you may call the principal investigator, who is the person in charge of this study and/or any other research team member listed below.

Principal Investigator:
Dr. Ivan Wong
Telephone: (902) 473-7626

Co-Investigators:
Dr. Tanya Keough, telephone: (902) 579-1599
Dr. John Kozey, telephone: (902) 494-1148

The Research Assistant:
Meaghan MacDonald (902) 473-2220, pager # 2910
Nicole Paquet (902) 473-7626

18. What Are My Rights?

You have the right to all information that could help you make a decision about participating in this study. You also have the right to ask questions about this study and your rights as a research participant, and to have them answered to your satisfaction before you make any decision. You also have the right to ask questions and to receive answers throughout this study.

If you have any questions about your rights as a research participant, contact Patient Relations at (902) 473-2133 or healthcareexperience@nshealth.ca. If you are calling us long distance (NS, NB and PEI), please use our toll free number 1-855-799-0990.

In the next part you will be asked if you agree (consent) to join this study. If the answer is "yes", please sign the form.

19. Consent Form Signature Page

I have reviewed all of the information in this consent form related to the study called: **Using a Computerized Potentiometric System for Anthropometric Measures (CPSAM) to Obtain Maximum Reach Envelope in Individuals with Full Thickness Rotator Cuff Tears - A Pilot Study.**

I have been given the opportunity to discuss this study. All of my questions have been answered to my satisfaction. This signature on this consent form means that I agree to take part in this study. I understand that I am free to withdraw at any time without affecting my future care.

I understand that all experimental trials will be video recorded for validation purposes. I have been informed that I am required to make a decision regarding the usage of the video and photographic material that is recorded during the completion of this research.

I voluntarily consent to video footage and photography being taken throughout the experiment for data analysis purposes.

Regarding the use of these images, please circle the appropriate response to which you agree. You have the ability to change this decision regarding the use of video or photographic material until 2 weeks after the completion of data collection.

The research team is free to use video or photographic records that include me for the purposes of knowledge translation, presentations, or publications. My identity will be masked. _____ (Initials)	No video or photographic material containing me may be used for any purpose other than data analysis. _____(Initials)

_____	_____	____ / _____ / ____
Signature of Participant	Name (Printed)	Year Month Day*
_____	_____	____ / _____ / ____
Signature of Person Conducting Consent Discussion	Name (Printed)	Year Month Day*
_____	_____	____ / _____ / ____
Signature of Investigator	Name (Printed)	Year Month Day*