Relationship between Shoulder Function and Maximum Reach Envelope

by

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With great thanks to my family for their support &

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Abstract

Background: Reach envelope or volume is the area in which a seated or standing human can reach. The maximum reach envelope (MRE) is performed with the trunk stable and the upper limb fully extended, thus shoulder mobility and function are key determinates. Persons with total rotator cuff tears have reduced range of motion and reach envelope capabilities, particularly with respect to horizontal and vertical motions at the periphery of the reach envelope. Ergonomic accommodations for an individual can be made to allow for potential return to work and assistance with activities of daily living if the limitations are known.

Objectives: To compare the MRE and the impact of small handheld loads on this for aged matched and college-aged adults with no history of shoulder injury (asymptomatic participants) and participants with total rotator cuff tears prior to and at several time points following surgical repair. This MRE will be used to define problematic areas of reach for symptomatic participant's pre and post-surgery to make recommendations for reasonable ergonomic accommodations to assist with activities of daily living and return to work.

Methods: Seated dynamic maximum reach envelope data was collected using the Computerized Potentiometric System for Anthropometric Measures (CPSAM) with 3 different handheld load condition (0.0, 0.5 and 1.0 kg) for 3 groups (young asymptomatic, age matched asymptomatic and persons with rotator cuff tears). Additionally anthropometric measures, range of Motions (ROM), strength, Disabilities of the Shoulder and Hand (DASH) and Western Ontario Rotator Cuff Index (WORC) survey data were collected for comparison between groups.

Conclusions**:** There are differences between reach and ROM capabilities of persons with RCT and asymptomatic, with a reduction in range of motion capabilities being reflected in a reduced reach envelope. This difference increases with the addition of hand held load, with the outer boundaries of reach showing the largest reduction. Accommodations for both workplace and activities of daily living (ADL) may be required to allow a person with a rotator cuff injury to maintain functionality, particularly when reaching in across the body and above the head.

Keywords: reach, maximum reach envelope, hand held loads, principal component analysis, rotator cuff tear, 3-D kinematics, ergonomics

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Chapter 1.0 Introduction

Ergonomics is the application of knowledge of human characteristics to the design of systems (Parsons, 2000). A comprehensive analysis of real-life working conditions requires the integration of a multi-disciplinary approach incorporating engineering, biomechanics and anthropometry (Schlick, 2009) to create designs that match with human complexity. There are many factors that can impact a human's ability to perform work effectively and safely in a given environment and the methods with which these abilities are measured vary widely. Most people work in complex environments and ergonomic methods are essential to create designs that limit a worker's physiological and psychological strain while maximizing productivity (Parsons, 2000). Since not everything is known about humans, the ergonomic knowledge base continuously grows and evolves. The principles and standards used also evolve to become more streamlined and predictive of the physiological, psychological and sociological elements that impact a human's relation to their work environment (Schlick, 2009). Some of the ergonomic principles to consider in a design include information on environment, anthropometric and biomechanical properties of the worker, interaction with machinery, tools and supplies, and the flow of work. This research will focus on the anthropometry and the biomechanical comparisons of reach for persons with shoulder injuries versus healthy shoulders as outlined in the framework shown in Figure 1.

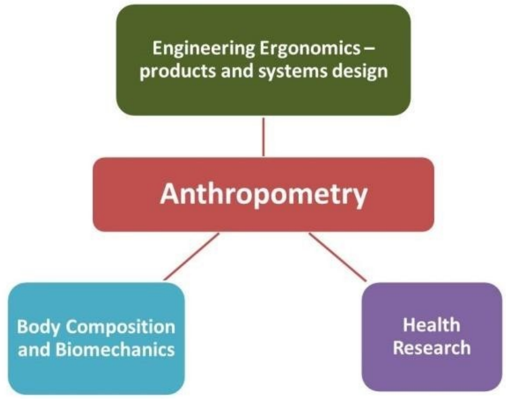


Figure 1: Project framework diagram

With respect to ergonomics, researchers know there are many intrinsic (body shape, segment length and range of motion) and extrinsic (clothing, body position and types of restraints) factors that can impact reach (Sengupta & Das 1998, Stoudt 1973). The shape of the reach envelope depends on the shoulder and elbow range of motion which may be impacted with the presence of injury or disease. Presently little is known about the impact any shoulder injuries may have on the reach envelope and if the reach may be regained following a surgical intervention, should surgery be necessary.

There are several approaches used to quantify the reach envelope of a person and to describe the reach of a population. Prediction models built on the basis of a combination of anthropometric measurements have been shown to be both possible and accurate (Das & Grady, 1983a; Stoudt, 1973, Reed, et al. 2006). This method is used by designers to evaluate humans and physical designs or create manikins to evaluate virtual designs and computer-based drawings. An early example of the measures of reach was in relation to the design of aircraft cockpits (Kennedy, 1964).

Mechanical devices specially designed with horizontal and vertical bars were used for the participant to touch, and researchers measured lengths related to a common seated referenced position (SRP). These methods were time consuming both in terms of data collection and analysis but also for applications to design. Das et al. (1994) created a computerized potentiometric system for anthropometric measures (CPSAM) that is useful for both structural measures as well as for dynamic (3-D) reach measures. The electromechanical system was able to determine positions in 3-D space with a reported accuracy of ±5mm. Having accurate reach measures for a population can be challenging as there are so many factors that can impact it, but creating designs that are suitable for a range of persons is important for safety and comfort. Generally, the authors reported that the attained accuracy would be suitable for most population-based studies.

From an Industrial Engineering perspective, most workspaces and work methods are developed based on healthy (asymptomatic) workers. However, there are many individuals who through occupational or other activities, suffer from musculoskeletal disease or injury during their career with shoulder issues only slightly behind low back in frequency (Reeves, 2018). Rotator cuff injuries are the most prevalent type of shoulder problem, accounting for up to 40% of all shoulder injuries (Jaeger et al., 2014) and they are more prevalent in older individuals. Rotator cuff injuries, particularly full tears or ruptures of one or more of the tendons, lead to severe pain, decreased range of motion (ROM) and loss of strength. These factors greatly affect the workers ability to perform many upper limb motions. Currently, little is known about the effect of this injury on ROM in particular, the maximum reach envelope (MRE) and even less is known about the effects of light hand-held loads on the MRE. Lastly, there is scant evidence of MRE measures post therapeutic / surgical treatments. In most cases pain, functionality, range of motion and strength all make significant improvements once the joint has recovered, however most patients still notice differences between their two shoulders (Sugaya et al. 2007). Knowing more about recovery would be beneficial for issues related to return to work.

The most common clinical technique for assessment of shoulder range of motion is goniometer measures. Goniometers have been shown to be reliable so long as the clinician is experienced, the patient is assessed by the same clinician at each appointment and there are standardized body positions for each measure (Hayes et al., 2001). A drawback of this measure is it is limited to planar values of flexion/extension, adduction/ abduction and internal/ external rotation. These values do not fully describe the complex motions that happen in most activities of daily living. This creates challenges when assessing patient functionality for return to work, and any required ergonomic interventions. There may be motions outside of these planar motions that are complex to capture without examination of the full reach envelope. The Computerised Potentiometric System for Anthropometric Measures (CPSAM) is a tool that can potentially assist in the assessment of a broader scope of functional reach measures, including reach envelope. The system uses the linear measurement of 4 recording devices to predict the position of a single point in a 3-D volume (Das et al., 1994). Data collection with the CPSAM are not time consuming and can yield values for active range of motion measures for current planar directions other than internal/ external rotation.

Activities of daily living and pain scores are also monitored through established surveys such as the Disabilities of the Arm and Hand (DASH) (Atroshiet al. 2000), or the Western Ontario Rotator Cuff Index (WORC) (Kirkley et al. 2003) that are completed by the patient. Scoring techniques such as the Constant – Murley Method (Constant & Murley, 1987; Gazielly et al. 1994) utilize observation methods that may vary slightly between observers but may be used to complement or replace goniometric measures. No equipment is required to complete these assessments, but the patient is asked to perform specific motions such as putting their hand on their head and then moving the elbow forward and back, reaching above their head, putting an arm behind the back to see how high can be reached. These values are then coupled with patient reported surveys of function during activities of daily living to create the patient profile and rate the necessity of surgery. There is currently no single objective functional measure that is universally used by all shoulder clinicians, nor do these assessments link to many occupational tasks.

Within the World Health Organization's Classification of Impairments, Disabilities and Handicaps different models are presented for describing function (World Health Organization, 2001). Figure 2 outlines some of the factors that can influence functional reach with a shoulder injury. This project will provide details with regards to arm lengths, ROM, Strength, posture and reach to begin to examine how these factors interrelate. This will better define participation limitations and begin to create a foundation for workplace and activity of daily living accommodations while an individual awaits surgical repair.

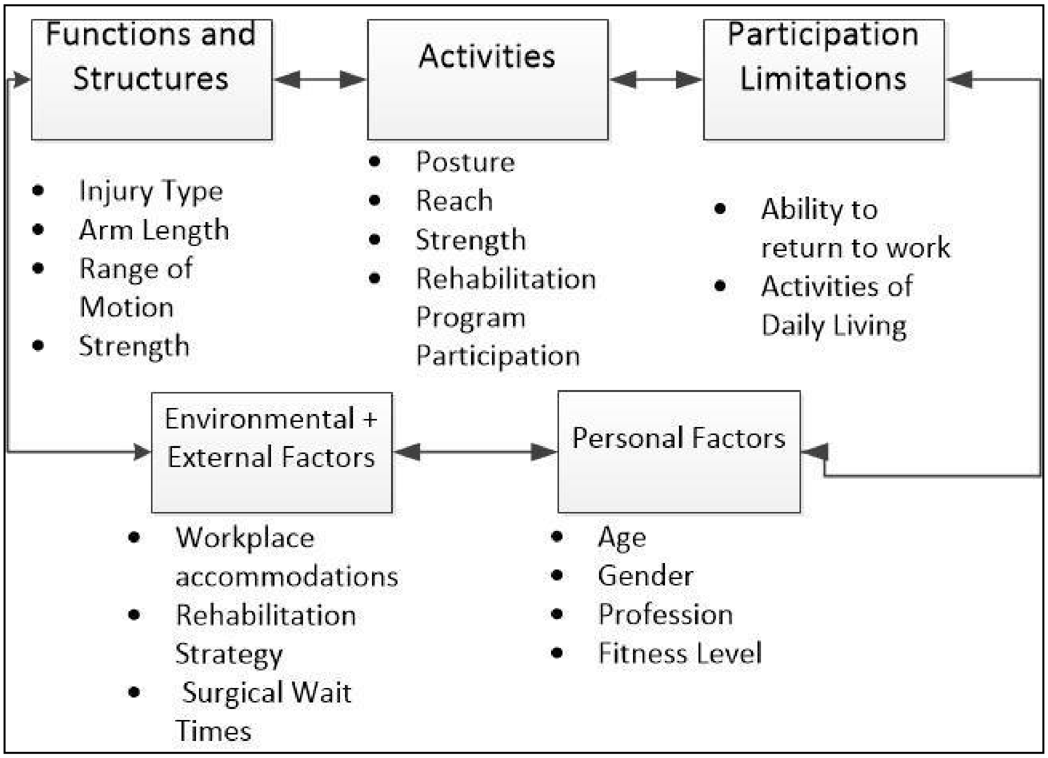


Figure 2: WHO International Classification of Function Framework for Rotator Cuff Injuries

In summary, techniques and measurement systems exist for the rapid and accurate collection of human reach. Workspace designs should attempt to incorporate these measures into the design phase and in many applications they do, but not in all. One gap in the literature is in the measurement and application of human reach into designs in which the worker/participants has a functional impairment (injury) to the shoulder. This can impact the inclusiveness of general designs as well as restricting return to work effort from individuals who have suffered a surgical or non-surgical injury to the shoulder.

1.1 Research Objectives

The overall goal of the investigation was to measure and compare the maximum reach envelope and the impact of small handheld loads on a group of symptomatic shoulder individuals compared to an age matched group with no history of shoulder injury (asymptomatic participants). The symptomatic participants had been diagnosed with total rotator cuff tears prior to initial testing, and it was intended to test them at select follow-up intervals (3, 6, 12 and 24 months post-surgical intervention). There has been little investigation or literature on the impact of shoulder injuries on the MRE; however it was thought that it will be reduced, particularly in regions at or above shoulder levels. The overall goal was achieved by addressing each of the following objectives.

Objective 1: To measure the reachable areas of the MRE for symptomatic participants pre and post-surgery to determine efficacy of rehabilitation, and to potentially make recommendations for reasonable ergonomic accommodations to assist with activities of daily living as well as return to work. This will be done through typical comparisons of the maximum reach envelopes, reach lengths and other anthropometric data to the asymptomatic participants, and pre and post-surgery values. Principal component analysis (PCA) was used to help define spatial reach patterns from the maximum reach envelope.

Symptomatic participants may need to bend their arms slightly to complete the reach tasks asked of them, particularly when reaching at or above shoulder height. It is expected that this will be more prevalent when handheld weights are added.

This may result in changes in the reach pattern of the MRE and will be reflected in the average reach lengths found for these regions. It is hypothesized that there will be significant differences in the measures of the MRE between asymptomatic and symptomatic participants.

Objective 2: To compare current clinical measures of shoulder function to values extracted from the MRE. Given the large volume of data collected including reach envelope measures, goniometer measures of range of motion, survey responses and anthropometric measures, a multivariate analysis in particular PCA was used to assist in data reduction. In general, PCA allowed for a reduction in the dimensionality of the data to fewer measures that represent the larger data set. PCA has been shown to be valuable in gait analysis to identify temporal patterns present in asymptomatic participants and those in various stages of osteoarthritis (Deluzio & Astephen, 2007). Through these patterns, clinicians are able to identify progression of osteoarthritis, and it is hoped that when applied to reach envelope, data patterns will emerge that can help with the rehabilitation of range of motion and reach.

For the long term, it is hoped this project can lead to the creation of a clinical measurement tool that can facilitate assessment and rehabilitation and be commonly accepted by all clinicians involved with patient recovery. This tool will expand current planar goniometer assessments into full reach volumes used by participants in activities of daily living and work activities which can then be related to workspace design and occupational ergonomic interventions.

Objective 3: To develop a series of knowledge translation tools useful to clinicians and patients alike that provide simple, relevant feedback on the functional status of the patient. At this point, the aim is to develop tools to the extent that future researchers could formally proceed with direct testing of their utility.

These objectives lead to the testing of the following hypotheses, stated in the null:

1. The addition of small handheld loads will not alter the MRE ofthe groups.
2. There will be no significant differences in the MRE between the groups.
3. Multivariate analysis of the MRE will show no differences in the MRE patterns between the groups (asymptomatic and symptomatic).

Chapter 2.0 Methods

2.1 Recruitment

2.1.1 Initial Recruitment Plan

To decide recruitment numbers and create age strata, basic participant demographics (shoulder injury group) were collected from a local clinical orthopaedic practice. Based on 64 patients, the mean age of the group was 59 ±9.4 years, for both men and women. Within the group, 30% were women with a mean age of 59± 8.3 years and 70% were men with a mean age of 58± 9.8 years. Based on these demographics, the normal distribution curve and typical results as reported in Johnston et al (Johnston et al. 2016) sample size and a stratified balanced design was developed. The goal was 20 participants per group, the desired recruitment ages were subdivided into 3 strata as described in Table 1. To ensure adequate female representation, females were oversampled slightly at a minimum of 40% of the sample. If this had not been done, there would have been strata with only one female tested. The value of 20 participants was determined based on the standard deviation and changes to median reach with load of the pilot data in spherical coordinates. Twenty participants per group (age matched asymptomatic and symptomatic) yields an approximate statistical power of 83.5%. The standard deviation was calculated from the root of the adjusted mean square error of the ANOVA to reduce the variability between load, subjects, phi band, and theta band of pilot data from college aged asymptomatic participants.

Table 1: Strata of Desired 20 Asymptomatic and 20 Symptomatic Participants

Strata	Age (Years)	Determined by:	Total N	Female	Male
1	≤ 49	<Mean- 1SD	4	2	2
2	50-69	Mean ± 1SD	12	4	8
3	>69	>Mean + 1SD	4	2	2
Total			20	8	12

Symptomatic patients were recruited through the Orthopaedics Shoulder Clinic at the Halifax Infirmary Hospital with the assistance of Dr. Ivan Wong, and no consenting participants were refused. Asymptomatic patients were recruited from the community at large using flyers, posters and social media. All testing was completed at the Biodynamic, Ergonomic and Neuroscience Laboratory (BEN Lab) at Dalhousie with research ethics approval from the Nova Scotia Health Authority Ethics Board. Prior to arrival, all potential asymptomatic participants were given the informed consent form to read and asked demographic questions to ensure they fit in a stratum. These 40 participants were combined with the young asymptomatic participants collected in the Honours Thesis research by Heather Johnston and Heather Rogers (Johnston, 2017; Rogers, 2018)

2.1.2 Actual Recruitment

Across the 3 groups, a total of 67 participants were tested. Of these, data from 61 was deemed usable based on their calibration curves from CPSAM. Of the 61, the breakdown of groups and their ages can be seen in Table 2. It can be seen that females were slightly oversampled in the young asymptomatic group, as these were more a sample of convenience collected prior to the testing of the symptomatic group.

Table 2: Participant Count and Mean Age by Group

Group	Count (N Female)	Mean Age (SD) Years
YASYM	20 (11)	24.2 (± 3.5)
ASYM	21 (10)	60.5 (± 10.4)
SYM	20 (8)	61.1 (±8.2)

The breakdown of age matched participants can be seen in Table 3, with the goal of males and females to be collected, and the actual number collected for each group shown. No symptomatic persons under 49 years old visiting the shoulder clinic met the study requirements during the collection time period, so there are no symptomatic participants in that strata. To account for this in the age matching to asymptomatic participants, more Strata 2 females were collected.

Table 3: Breakdown of Strata Size for Age Matched Participants

		Females			Males		
Strata	Age Range (Years)	Goal	ASYM	SYM	Goal	ASYM	SYM
1	≤ 49	2	2	0	2	2	0
2	50-69	4	6	6	8	7	10
3	>69	2	2	2	2	2	1
TOTALS		8	10	8	10	11	11

2.2 Data Collection

Prior to the arrival of a participant, all equipment was checked and calibrated by researchers in accordance with the CPSAM Procedure Manual. This includes ensuring that all springs in the potentiometric recording units (PRUs) are properly re-coiling the strings, the pulleys are running freely, and the potentiometers are within the ±10 volt range.

Upon arrival, the informed consent form was reviewed with all participants, and they were given an opportunity to ask questions and asked to provide informed consent. Symptomatic participants underwent the consent process during their clinic visit, and this form was forwarded on to researchers, however consent was reviewed, and opportunities for questions given.

2.2.1 Auxiliary Measures

Symptomatic participants completed several questionnaires online as part of their assessment with the clinic: the Western Ontario Rotator Cuff Index (WORC), and Disabilities of the Arm, Shoulder and Hand (DASH) the ORTECH online system. These were also completed by asymptomatic participants following their testing session.

Standard clinical passive and active range of motion measures were taken with a goniometer following the procedure used clinically as outlined in Appendix B. These measures were completed with the person either supine or standing as noted and were completed prior to the reach testing. The tests for internal/ external rotation follow the Constant-Murley Scoring method previously mentioned. Following the reach testing, a series of isometric strength assessments was taken using a Mark-10 Force Gauge Model M3-200 of the injured limb, following the clinical protocol which used the mean of 3 trials for each measure. Basic anthropometric measures of arm length, segment lengths, and height were measured using a stadiometer, body mass was measured using a scale. Each of these measures was taken once. These data were collected with the assistance of an experienced research assistant to ensure reliability of the measures. Data was collected on the right (dominant) arm of all participants, with the exception of 5 symptomatic participants with injured left shoulders. The collection forms used can be seen in Appendix C.

2.2.2 Reach Measures

Each participant was given an opportunity to familiarize themselves with the 3-D reach measures with each of the 3 weights; 0.0 kg, 0.5 kg and 1.0 kg. The participants were then seated in the forward-facing position and static collections of the acromion, zyphoid process, sternal notch and elbow positions taken using the CPSAM stylus. Each position was collected using LabView software for analog-digital conversion at 20Hz, with a 5 second trial. For the reaching trials, two trials of each of the 3 weight conditions were collected. Each trial lasted 45 seconds with a sampling rate of 20 Hz. During the trial participants were asked to repeatedly trace the outer boundaries of their maximum reach and then asked to "paint" within the area. This movement was completed at a self-selected pace, and participants were encouraged to keep the upper limb as extended as possible throughout. The order of presentation of the loaded (0.5 and 1.0 kg) conditions were randomized for each participant, all participants started with a 0.0kg load condition. The chair position was then rotated 90^{o} to the left (or right for left-handed symptomatic participants) to allow for collection of side reach. Measures of the chair and anatomical points were repeated prior to the reach trials.

It was expected that symptomatic participants may have difficulty maintaining a fully extended arm when reaching above shoulder height, particularly with weight, but were encouraged to do their best. Several of these participants were not able to complete parts of the weighted testing, or weighted testing was limited due to participant discomfort. Participants were given at least 30 seconds, up to 2 minutes rest between trials to ensure that they were not fatigued, but this time was self-selected by the participant. At the end of the collections, participants were given an opportunity to ask any follow-up questions they may have and were de-briefed prior to departure.

Symptomatic participants were asked if they would like to return for a follow-up assessment 12, 24 and 52 weeks post-surgery. At this time the entire procedure would be repeated as above. Most consented to be contacted for follow-up, however only 2 participants participated in follow-up testing at the time of this document; one at 12 weeks, and one at 52 weeks.

2.3 Data Processing

Data processing was performed using custom Matlab programs, Microsoft Excel, Microsoft Powershell and Minitab for statistical and principal component analysis. All anthropometric, range of motion, and strength measures as well as the result of the questionnaires were input to spreadsheets for general comparison and descriptive statistics. The maximum and minimum angular (Phi) values in each statistical band were found for use in principal component analysis to determine temporal patterns and relationships between groups. Custom Microsoft Powershell Scripts were created to read the processed statistics and PCA files and concatenate them into one master CSV file for each type of coordinate system. This was to minimize copy/paste errors, and streamline processing.

There were several methods by which data was examined during and following processing. Several graphical outputs were included in the programs to allow for visual checks, in addition to the measures taken to ensure good data prior to and during collections. The calibration curves relating voltage to length were checked for linearity, the chair points were visually prior to and post rotation to ensure proper spacing and rotation, and finally the overall MREs were graphed to ensure that all points had been rotated correctly, and to ensure minimal outliers. Outlier points can occur on the inner portion of the MRE if someone bends their elbow or on the outside if there are problems with a particular reach trial. Data from several participants was found to have problems in processing and was not able to be used in the study (ASYM003, ASYM016, SYM007 and SYM009).

2.3.1 Auxiliary Measures

Each of the passive and active range of motion, strength and anthropometric measures were entered into a Microsoft Excel Spreadsheet, which includes demographic information regarding the participant. In the clinical assessments, the metric for external and internal rotation uses the Constant-Murley Method, and values from 1-5 have been assigned to each location as shown below **Table 4** to allow for statistical comparisons.

Table 4: Scoring Conversion of Constant- Murley Evaluation

External Rotation	Internal Rotation	Score
Hand behind Head, Elbow forward	Buttock	1
Hand behind Head, Elbow back	Lumbosacral Junction	2
Hand to top of Head, Elbow forward	Waist (L3)	3
Hand to top of Head, Elbow back	T12 Vertebra	4
Full Elevation from top of Head	Interscapular (T7)	5

These data were imported to Minitab for statistical analysis. It was noted during testing that not all symptomatic participants were able to be easily scored using the 1-5 rating above, as some persons could complete 1, 2 and 5 but not 3 or 4.

2.3.2 Reach Measures

Reach measures were processed, as previously discussed, with 3 dimensional Cartesian coordinates translated into cylindrical and spherical coordinates with an origin at the acromion. The cylindrical data was partitioned into 6 z-bands (horizontal divisions), and 9 theta (θ) bands which are angular bands that cover the maximal range of motion for the shoulder through horizontal flexion. An example of these divisions can be seen in Figure 3. After partitioning the data; the frequency, mean, median and standard deviation of the reach length in each bin was calculated. The radial length of the reach was calculated using the following equation:

$$R_{CYL} = \sqrt{x^2 + y^2} \quad [1]$$

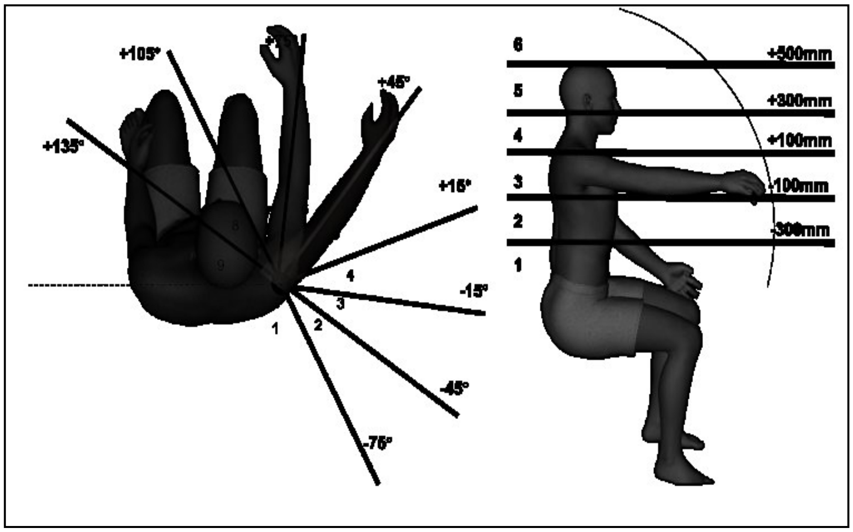


Figure 3: Theta and Z band divisions

The spherical data was sub-sectioned into theta (θ) bands, similar to those in the sagittal plane of cylindrical coordinates, and phi bands (φ) which extend through flexion and extension. An example of the theta and phi band divisions can be seen in Figure 4.

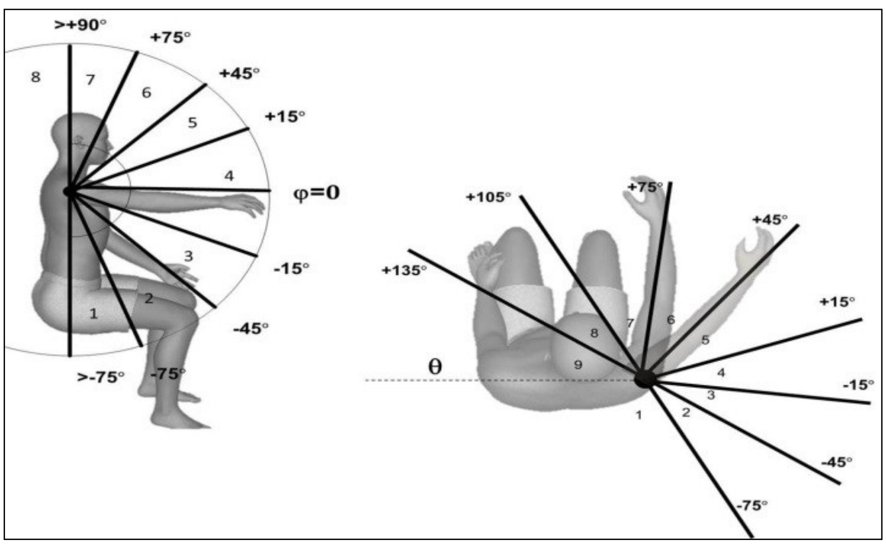


Figure 4: Phi and Theta band divisions

Within the bins for the spherical coordinates, the reach length was calculated for all points in the bin using equation 2:

$$R_{Sphere} = \sqrt{x^2 + y^2 + z^2} \quad [2]$$

Where $x = x_{pointer} - x_{acromion}$ and similarly for y and z. For all points in each bin the frequency, mean, median and standard deviation of the reach length was determined. Data were then concatenated using custom PowerShell programs.

A secondary measure was developed to quantify areas within the MRE accessible by participants in the three groups. This was performed using the spherical and cylindrical statistics previously completed. This method uses binary yes or no analysis to determine if a bin was accessed by the participant. For each bin with no data points the score is 0 and for those with at least one data point there is a score of 1. Using these scores reach maps were created which are visual representations of where participants can or cannot reach. It is thought that this may be a good knowledge translation tool for both clinicians and participants. Currently, these are 2-D and do not account for changes in reach length or the frequency each of the bins was reached, they are simply binary yes or no values. An example of a 2-dimensional colour map can be seen in Figure 5. This map is for 10 pilot participants, and red indicates regions no one reached, while bright green indicates regions everyone reached. There is a gradient scale indicating regions where some participants reached but not all. Knowing common regions of reach ability gives feedback to clinicians and patients alike.

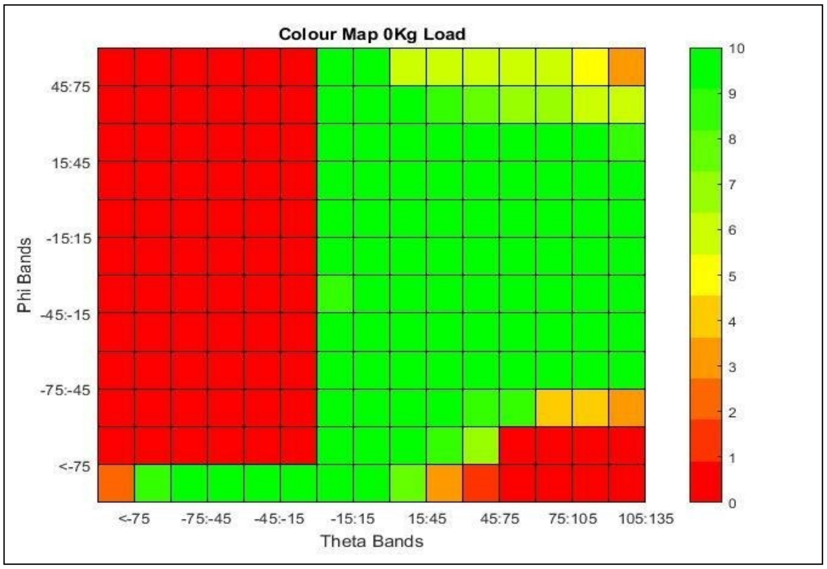


Figure 5: Sample colour map of 10 pilot participants

2.3.3 Principal Component Analysis

A principal component analysis (PCA) examining the inherent reach patterns was also completed. For each of the theta bands (in both cylindrical and spherical coordinates) the 3 maximum and minimum Z/ phi values were determined. If there were less than three values in a band, no value was put forth. These values were then imported into Minitab and examined separately, with regards to the PCs resulting from each group.

PCA has been used to demonstrate differences in temporal waveform patterns in gait of asymptomatic and progressive levels of knee osteo-arthritis with great success (Deluzio & Astephen, 2007). Due to the large amount of data collected during gait analysis, reducing the data and interpreting the data can be challenging without PCA. PCA is helpful in summarizing key points through representing the variables through a limited number of optimal principal features found through orthogonal transformation into eigenvectors of the covariance matrix (Deluzio & Astephen, 2007). Reach envelope does not follow the same repeatable, predictable pattern that is found in gait, but it does have large numbers of related data points that could benefit from data reduction.

This chapter has presented the overall summary of the methodology for this study. The next chapter of the dissertation will be presented as preliminary manuscript documents with specific data related to the chapter as appropriate.

Chapter 3.0 Comparisons of the Maximum Reach Envelope across 3 Groups

3.1 Introduction

Human reach envelope, both normal and maximal, as has been defined (Konz & Goel, 1969) as the area (volume) in which a seated or standing human can reach while performing a task. Execution of the maximum reach is performed with the trunk stable and the upper limb fully extended, thus shoulder mobility and function are key determinates of the motion. Typically, reach and the reach envelope have been examined by collecting empirical data or by creating mathematical models. Researchers know there are many intrinsic (body shape, segment length and range of motion) and extrinsic (clothing, body position and types of restraints) factors that can impact reach (Sengupta & Das, 1998; Stoudt, 1973). People vary and one model will not suit all persons (Konz & Goel, 1969). The critical boundary for reach without any other body movement is proportional to a person's arm length (Carello et al. 1989; Choi & Mark, 2004; Heft, 1993; Mark et al., 1997). Research has also shown that by designing workspaces where all movements are encompassed within the 95th percentile for a population's maximum reach envelope (MRE) can limit injury risk (Faulkner et al, 1970).

The shape and volume of the reach envelope also depends on shoulder and elbow range of motion which may be impacted with the presence of an injury or disease. However, there is little empirical evidence of the impact of shoulder injuries on the reach envelope and if the reach may be regained following a surgical intervention. Similarly, there have been very few studies that attempt to relate the MRE to clinical measures of shoulder ROM.

The maximum upper limb working area was defined by Lowry et al (1940) as the distance that can be reached by the fully extended arm as it pivots about the shoulder, with the normal working area as the space that can be reached by the forearm when it pivots around a relaxed vertical upper arm (Lowry et al.1940). Barnes (1963) defined the normal working area as an arc drawn with a sweep of both hand and forearm with the upper arm hanging by the body in a natural angle, with the area where the two arcs intersect constituted the area in which two handed work should be performed. Farley (1955) thought of the reach volume as a sphere, with the radius being the arm length of the. Squires (1956) noted the elbow moves away from the body as the forearm pivots, which compared to the Farley curves (Das & Grady, 1983b) yields greater accuracy in predicting work area.

To account for anthropometric differences, Konz and Goel (1969) used data from the National Health Survey of over 11000 men and women between the ages of 18 and 79 to find the 5^{th} and 95^{th} percentile values for body height, upper arm length, forearm length and elbow to shoulder projection difference. They directly measured 40 men and women who fell into each quartile of these ranges to create their own curves for normal work area. These can be seen in Figure 6.

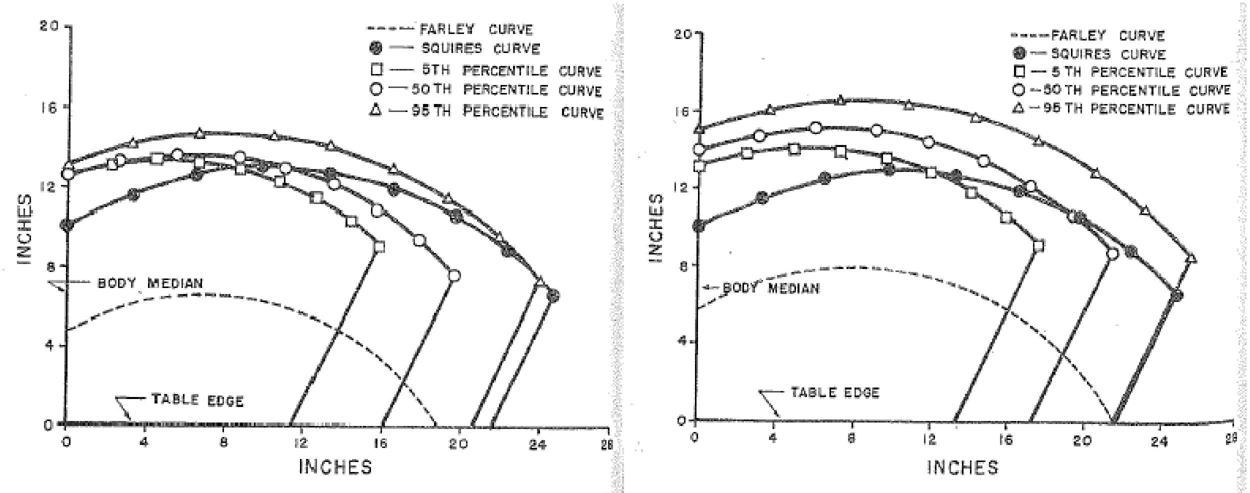


Fig 5. Proposed normal work area for males. Fig 6. Proposed normal work area for females.

Figure 6: Comparing Farley, Squires and Konz's curves of normal work area for males and females

Faulkner and Day (1970) noted the reach envelope can be directly impacted by chair height and position, the size of the weight being lifted, the type of grip used on an object as well as the posture of the worker during the trial (Faulkner & Day, 1970), although they do not specify the exact impact that these will have.

Kozey (1996) calculated the 5^{th}, 50^{th} and 95^{th} percentile reach values for both male and female wheelchair users. The data was collected and processed initially using the Cartesian coordinate system, but was converted into cylindrical coordinates (θ, R, Z) and subsequently divided into bins where θ was broken into 10^{o} intervals for each X-Y plane, and Z levels were divided into 100mm bands, beginning at the surface of the table. This allowed them to determine the mean projected radial length for each participant. A regression analysis was then performed to yield prediction equations utilizing Z and θ for the reach envelopes of a 5^{th}, 50^{th} and 95^{th} percentile male and female population which took the form shown in Equation 3.

The subscripted β are known values described by Kozey in his dissertation (Kozey, 1996).

$$\beta_0 + \beta_1\theta + \beta_2\theta^2 + \beta_3 Z + \beta_4 Z^2 = \text{Radial Length} \quad [3]$$

Additionally, graphs of the predicted path were created for each respective Z-level, with an example being shown in Figure 7. It can be noted that these graphs are similar to some previous curves, with the important note that only the right arm was examined, and it was shown that it can pass in front of the body midline, but not as far as was previously indicated by Faulkner and Farley.

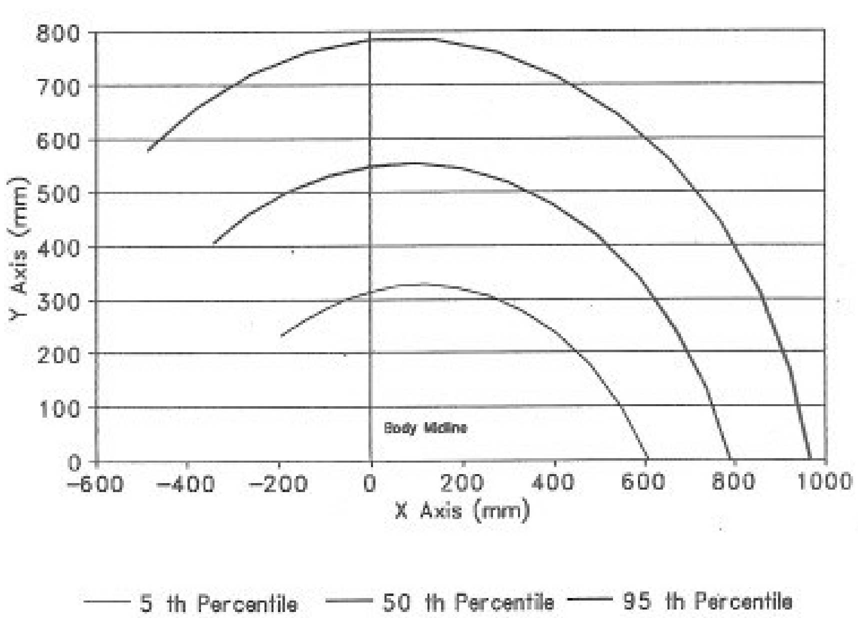


Figure 7: The 5th, 50th and 95th percentile reach envelope for males at table height

In subsequent work utilizing CPSAM, Das and Sengupta investigated modelling the entire point cloud using spherical coordinates as opposed to a cylindrical. This builds upon the work done by Farley and capitalizes on improvements in computer processing. Using points collected by the CPSAM, Sengupta and Das (1998) used non- linear optimization to fit a sphere to the data, utilizing equation 4.

$$SE = \sum_{j=1}^{j=n}\left(\sqrt{(X_C - X_j)^2 + (Y_C - Y_j)^2 + (Z_C - Z_j)^2} - R_j\right)^2 \quad [4]$$

The subscript j represents the collected data points, R_j is the estimated radius at each point, and (X_c, Y_c, Z_c) represents the estimated center of the sphere. The goal of the optimization is to minimize the sum of the error differences (SE) (Sengupta & Das, 1998). An overall error was found to be within 3cm in both standing and seated positions, but this does not take into account where in the MRE the error is taking place.

Kozey revisited the spherical modelling method with the objective of determining where in the MRE the error occurred, in addition to validating the robustness of the model with fewer points. In this work persons were tested, with spherical models fitted to their MREs, and then data reductions were done to limit the number of points being put into models (Kozey, & MacKenzie, 2002). The error in the model was found to be very low in the center regions of the MRE, with reported errors of less than 5mm, however on the outer regions the error significantly increased to more than 25mm which is similar to what was previously reported by Sengupta (Sengupta & Das, 1998). It was also shown that in order to maintain this accuracy, the previous 2700 or 1800 data points are not required, and that as few as 10 data points still yielded similar model results if the proper points were chosen.

One of the potential sources of the error in the outer regions of the MRE is simply that the glenohumeral joint is completely static when the arm is in motion, meaning that origin of the sphere is not fixed in space. This is one of the ongoing issues with any sort of biomechanical modelling of the upper limbs; there is not only rotation, but some translation of the joint centre within joint, despite the best efforts of researchers to fix it in place during testing. There are guidelines for overall shoulder, elbow and wrist range of motion characteristics, but it is not possible to create one single model that will accurately describe every possible human arm motion.

A crossover between ergonomics and health research occurs when creating work accommodations for injured persons. Rotator cuff tears are the most prevalent shoulder injury accounting for 40% of all shoulder injuries, (Jaeger et al., 2014) and prevalence increases with age. Rotator cuff injuries, particularly full tears or ruptures of one or more of the 4 SITS muscles (supraspinatus, infraspinatus, teres minor and subscapularis) lead to severe pain, decreased mobility and loss of strength. Human reach envelope is one method ergonomists use to define work areas. A person's ability to complete their activities of daily living, particularly work tasks, can be impacted by their reach envelope, as described in the World Health Organizations International Classification of Function framework (previously discussed) however there are currently no guidelines for designing or accommodating persons with shoulder impairments.

Objectives for this section include defining the differences in the 3-dimensional MRE for 3 groups under 3 separate load conditions (0.0, 0.5 and 1.0 kg):

- young asymptomatic (YASYM)
- age matched asymptomatic (ASYM)
- symptomatic (SYM)

Symptomatic participants were recruited through a local orthopedic clinic and were pre-surgical repair for large rotator cuff tears. Methods for translating the data to be more useful in clinical applications will also be explored.

3.2 Methods

Maximal reach envelope data was from a sample of young and age matched symptomatic persons as per the table below. However, there were issues with post- processing with several data sets, so the actual total is also included. Another note is that for 5 of the young asymptomatic participants, only 2 of the 3 load conditions were tested, so in later discussions fewer data points will be found in the 1.0kg load condition results.

Table 5: Group recruitment

Group	Collected (N Female)	MRE Data (N Female)	Mean Age (SD) Years
YASYM	20 (11)	16 (10)	23.8 (3.1)
ASYM	21 (10)	21 (10)	60.1 (10.3)
SYM	21 (9)	19 (8)	61.4 (8.3)

Each participant was given an opportunity to familiarize themselves with the 3-D reach measures with each of the 3 weights; 0kg, 0.5kg and 1kg. The participants were then be seated in the forward facing position and static collections of the acromion, zyphoid process, sternal notch and elbow positions were be taken. Each will be collected using LabView software for analog-digital conversion at 20Hz, for a 5 second trial. For the reaching trials there were two trials of each of the 3 weight conditions were collected.

Each trial lasted 45 seconds at a sampling rate of 20 Hz. During the trial the participants were asked to repeatedly trace the outer boundaries of the maximum reach and then asked to “paint” within the area. This movement is completed at a self-selected pace, and participants are encouraged to keep their elbow as extended as much as possible throughout. The order of presentation of each load conditions were randomized for each participant, however always started with a 0kg load condition. The chair position was then rotated 90 to the left (or right as required) to allow for collection of side reach. The chair and anatomical points were repeated prior to the reach trials (Johnston et al., 2016).

It was expected that the symptomatic participants would have difficulty maintaining a fully extended arm when reaching above shoulder height, particularly with weight, but they were encouraged to do the best they could. If necessary, the participant was told to take their arm back down to rest on their knee so data could be clipped at the proper frame. At the conclusion of the front facing trials the chair was then rotated 90^{o} so that the symptomatic arm is facing CPSAM, the 3 chair positions were collected, then the participant was seated and the procedure repeated again. Participants were given between 30 seconds and 2 minutes between trials to ensure that they were not fatigued. At the end of the collections participants were given an opportunity to ask follow-up questions they may have and were de-briefed prior to departure.

Data was processed using custom programs in Matlab to determine 3-D Cartesian coordinates. The 3-D Cartesian values were translated to an origin at the acromion and expressed in both cylindrical and spherical coordinates. This volume space was then paneled into 54 reach bins in cylindrical coordinates (6 z levels and 9 θ bands), and spherical coordinates with (6 φ bands and 9 θ bands, see Figure 8). Analysis was completed on both coordinate systems; however spherical coordinates were deemed more applicable to the desired outcomes, so it will be the focus.

All data points within each bin were used to calculate a median reach length. Additionally, the total counts (occurrences of reach) and standard deviations of these were calculated.

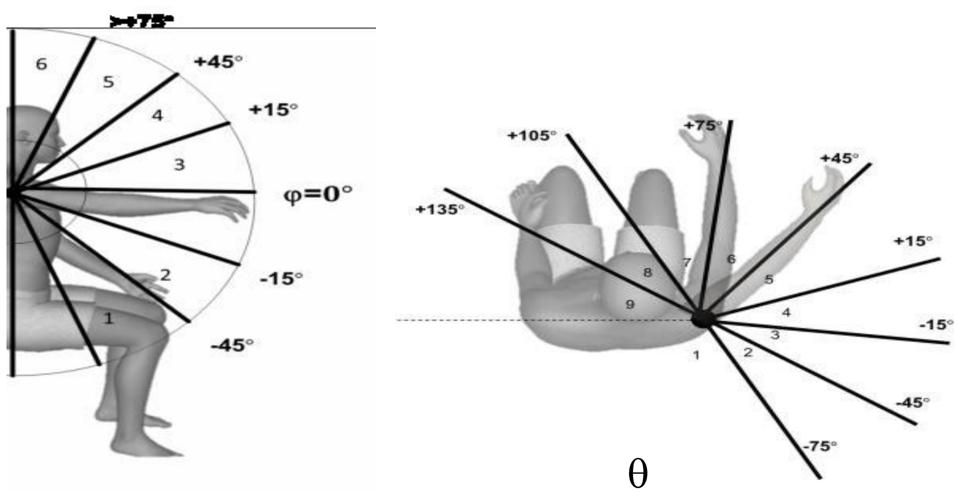


Figure 8: Spherical coordinates (phi and theta)

The overall statistics files for each load condition were then taken into Minitab for statistical analysis including tests for normality, Johnson and Box-Cox transformations, general linear models and Tukey Post-hoc analysis.

3.3 Results

Each of the 3 groups was similar in mean heights and weights, with the age matched asymptomatic group having slightly longer mean arm lengths, but no significant difference ($p > 0.05$).

Table 6: Group anthropometrics

Group	N	Age (SD)	Height (SD) (mm)	Weight (SD) (kg)	Arm Length (SD) (mm)
YASYM	16	23.8 (3.1)	1714 (94)	79.4 (19.9)	728 (48)
ASYM	22	60.1 (10.3)	1706 (147)	83.7 (23.1)	753 (53)
SYM	19	61.4 (8.3)	1692 (110)	83.0 (18.7)	726 (49)

The median reach lengths for all data were found not to be normally distributed ($p<0.005$), however the histogram (with n=3296 samples) is visually close.

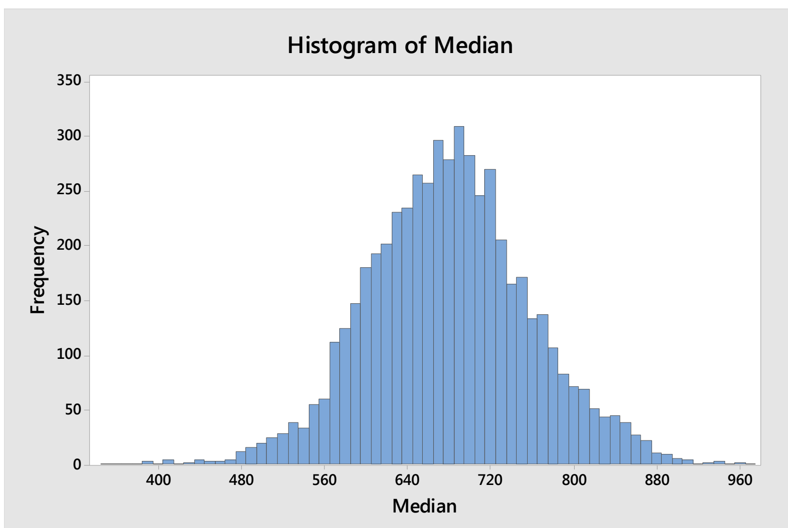


Figure 9: Histogram of full spherical data (medians)

The descriptive statistics were computed and are summarized in Table 7.

Table 7: Summary of full spherical data set

Group	$N_{reached}$	$N_{missing}$	$N_{potential}$	Mean (SD)
YASYM	1651	563	2214	677 (78.4)
ASYM	2387	1015	3402	694 (71.9)
SYM	1309	1661	2970	659 (84.8)

Of particular interest in Table 7 is the number of missing values compared to the not missing values. This will be discussed in detail later, but note less than half of the bins have values in the symptomatic population. As the medians were not normal, a general linear model was done using a Box-Cox Transformation with median as the response and group, load, phi and theta as inputs with interactions up to level 2. It should be noted that in Minitab 18, when using a Box-Cox transform in the GLM the optimal is used in the background calculations, but none of the transforms are displayed unless requested, meaning the post-hoc analysis stay in the original units. From Tukey post-hoc analysis, there were differences in the means of the medians of each of the 3 groups with the age matched group having the largest (702 mm), the symptomatic group being smaller (668 mm) with the young asymptomatic group in the middle (681 mm). The pairwise comparisons for load showed that there was very little overall difference between the 3 load conditions; however the interaction of group with load yields interesting differences (Table 8).

Table 8: Group by load interaction term comparison

Group*Load	N	Mean(mm)	Grouping		
ASYM 1.0 kg	792	706.7	A		
ASYM 0.5 kg	787	706.6	A		
YASYM 0.0 kg	652	694.0	A	B	
ASYM 0.0 kg	808	693.1		B	
YASYM 1.0 kg	398	675.2			C
YASYM 0.5 kg	601	674.1			C
SYM 0.5 kg	435	671.8			C
SYM 1.0 kg	391	670.5			C
SYM 0.0 kg	483	662.8			C

Means that do not share a letter are significantly different.

The two loaded conditions for age matched asymptomatic and the no load condition for the age matched are similar in reach lengths. The no load condition is similar between the young and age matched asymptomatic groups, with the 5 remaining load combinations all having similar means. Of note is for the symptomatic condition with full data sets, the mean of the 0.5 kg load condition was larger than the 1.0 kg and no load. These results were repeated using a Johnson transformation prior to the GLM calculation with the same results.

In the above model, one of the major limitations is that statistical analysis cannot be performed on missing data, and no overall load differences were detected in the full 54 bins which does not lend insight into specific regions of differences between groups. To better focus on regions where data was present versus missing, tallies of each load by group were created with the focus on symptomatic participants. Figure 10 displays the counts of how many of the 19 participants were able to reach each of the 54 bins. It can be seen that all of phi bands 5 and 6 (60^o and 75^o on y axis) had very low counts. Additionally, theta bands 1, 2 and 9 (-75^o, -60^o and 135^o on the x- axis) had more than 50% missing data. These patterns of data were also seen in the 0.5 kg and 1.0 kg conditions, but with even lower counts in several bins. It was decided to remove these regions from the analysis for all 3 groups, which leaves 24 bins.

Table 9: Bin counts for symptomatic participants with 0.0 kg load

		Θ (Deg)								
		-75	**-60**	**-30**	**0**	**30**	**60**	**90**	**120**	**135**
φ (Deg)	**75**	1	1	2	3	3	4	4	1	2
	60	0	1	6	10	10	12	12	9	4
	30	0	2	9	14	15	17	17	17	8
	0	0	2	9	17	17	17	19	18	10
	-30	0	3	10	16	17	19	19	19	11
	-60	0	5	10	15	14	15	11	4	2

The pared down data missing values were then compared to the initial missing value by load, with drastic differences. In group 3, symptomatic participants now had more bins with data than without (Table 10).

Table 10: Missing and non-missing data counts by load and group before and after data paring

Group	**Counts**	**No Load**		**0.5 Kg**		**1.0 Kg**	
		Full	Pared	Full	Pared	Full	Pared
YASYM	N	652	361	601	337	398	227
	Missing	212	23	209	23	142	13
ASYM	N	808	464	787	460	792	465
	Missing	326	40	347	44	342	39
SYM	N	483	355	435	323	391	304
	Missing	543	101	537	109	581	128

Statistical analyses were then repeated, with the median still not normally distributed. The means (Table 11) are comparable to the full data set.

Table 11: Pared data means and standard deviations

Group	Mean Reach(SD) (mm)
YASYM	672 (80.0)
ASYM	695 (71.4)
SYM	653 (85.1)

Both a Box-Cox and Johnson transformation were used to transform data for the GLM (separately), with the median being the response and group, load, phi and theta with interactions up to second order as the factors. Results with both transforms were the same. The 3 groups were found to be different using the Tukey pairwise comparisons, with ASYM having the largest mean, and SYM having the smallest. For the 3 load conditions, there was now a difference between the 1.0 kg load and the 2 other conditions. Of these, no load had the longest mean reach length, and 1.0 kg had the smallest, with a difference of about 10mm. The group by load interaction is still complex, but greater differences in the means are seen with the pared data (**Table 12**).

Table 12: Group by load interactions on pared data

Group*Load	N	Mean (mm)	Grouping		
ASYM 0.5 kg	460	699.0	A		
ASYM 1.0 kg	465	698.0	A		
ASYM 0.0 kg	464	690.0	A		
YASYM 0.0 kg	361	689.3	A		
YASYM 0.5 kg	337	666.7		B	
SYM 0.5 kg	323	654.5		B	C
YASYM 1.0 kg	227	653.1		B	C
SYM 0.0 kg	355	648.6			C
SYM 1.0 kg	304	645.8			C

Means that do not share a letter are significantly different.

All of the age matched load conditions plus the YASYM 0.0 kg load were found to be similar with the largest reach lengths. The lowest reach lengths were seen with the symptomatic and 1.0 kg load for young asymptomatic participants. There was a moderate reach group containing the 2 loaded conditions for the young asymptomatic and the 0.5 kg load of symptomatic participants. In the pared condition there was also some differences seen in the phi bands, with the 2 lowest (-75^o to -15^o) having larger reach lengths than the 0^o or 30^o bands. The 0^o and 30^o bands also differ, with the higher arm having smaller reach lengths.

With raw medians being used for this analysis, there was still some impact of arm length on the reach length. To account for this, the reach values were normalized into percentage of arm length using the arm length of each individual participant. This normalization process is described in further detail in Appendix D. These normalized values were used as the response to create a GLM with factors as above. With the normalized arm values it was found that the means of the age matched and young asymptomatic groups were similar (92.6% and 92% respectively) with the symptomatic having a smaller mean of 89.7% of arm length. Within the 3 load conditions, the no load and 0.5 kg load are still similar with 92.1% and 91.7% reach, with the 1.0 kg load being 90.4%.

When looking at the interaction of the group by load factor, 4 distinct groups are seen (Table 13). The young asymptomatic with no load has the longest reach with 94.8%. This is followed by the 3 load conditions of the age matched and the 0.5 kg condition of the young asymptomatic (ranging from 93.0% down to 91.8%). The 3rd group, with the age matched 0.0 kg, and the 0.5 kg loads of the young and symptomatic participants (91.9% to 90.4%). The 4th group contains the 3 symptomatic load conditions, and the 1.0 kg condition of young asymptomatic participants (90.4%-89.0%).

Table 13: Pairwise comparisons of group by load interactions in pared spherical data

Group*Load	N	Mean (% AL**)	Grouping			
YASYM 0.0 kg	361	94.9	A			
ASYM 0.5 kg	460	93.0		B		
ASYM 1.0 kg	465	92.9		B		
ASYM 0.0 kg	464	91.9		B	C	
YASYM 0.5 kg	337	91.8		B	C	
SYM 0.5 kg	323	90.4			C	D
SYM 0.0 kg	355	89.7				D
YASYM 1.0 kg	227	89.5				D
SYM 1.0 kg	304	89.0				D

Means that do not share a letter are significantly different.

** %AL= Percent Arm Length

3.4 Discussion

Reach measures represented in spherical coordinates were the main focus of the analysis to reduce the number of non-reached bins. It was known that there were going to be regions of the MRE that were difficult or impossible for the symptomatic participants, but currently published ROM values are only in planar directions, which limits the understanding of reach work area for the arm. It can be hard to extrapolate ROM values into a MRE that accurately reflects what the shoulder can do when injured. This study was the first to look at the full dynamic ROM for participants with RCTs. Pilot work showed large variations in what persons with RCTs could do in terms of the full reach envelope, and the 9 theta and 6 phi bins were adjusted slightly to reflect this, but more data was needed to confirm. Paring down the data to focus on the more central, normal work area made statistical analysis possible.

For the 24 remaining bins, the age matched asymptomatic participants had the largest mean reach in all 3 load conditions, with the no load condition for the young asymptomatic being comparable. The young asymptomatic 1.0 kg load condition was statistically the same as the symptomatic group for all conditions. This shows a reduction of 3.3% between the no load and 0.5 kg conditions, and 5.3% to the 1.0 kg condition there is the greatest change in reach volume for young asymptomatic participants when adding loads. There may be some psychological basis for this outside of the scope of the study, or there may be a physiological reason. The majority of the young asymptomatic group was female, and it is known that females may not be as strong as males (Robinson et al. 2017a). Unfortunately, no strength measures were taken for these pilot groups to be able to compare with the age matched asymptomatic strengths. When the raw reach lengths were normalized to arm length, the overall load and group interactions changed slightly with the young asymptomatic having the largest percent arm length reach at 94.9% with no load, but this group still had the most drastic changes the addition of handheld load.

Another point of interest to arise from this comparison was the load condition in which both the age matched asymptomatic and symptomatic groups presented. Both groups had the longest reach with the 0.5 kg load condition, although the differences between the 2 loaded and unloaded conditions were minimal at 1.1% or less of arm length. There was a difference between the two groups, with the age matched asymptomatic group having reach up to 4% larger than the symptomatic group. This is important for designing tasks, as it highlights that the chosen reach length in the maximum working area is consistently less than arm length, and can be up to 11% less. Increasing the distances means designing tasks that involve extreme reach will require trunk movement if the participant is seated, which can increase the risk of sustaining injury, such as low back pain (Keyserling et al., 1988).

3.5 Summary

Participants were encouraged to maintain a fully extended arm where possible, but there may be regions where the elbow bent slightly and gave shorter reach lengths. Using this extended arm does test the worst case scenario with the handheld weights, as the moment arm created around the shoulder is the greatest. Bending the elbow and moving the weight closer to the body may allow the person to lift, but lowers the maximum reach lengths.

The impact of load was minimized by paring down the data heavily in both coordinate systems, as it focused on areas where more persons could reach, so that there were enough values to do a statistical analysis. It can be seen in the reach maps, where the data was not pared down, that there was a large load effect. It begins with the outermost regions of the MRE, and the 1.0 kg load condition had major impact for the symptomatic group. Knowing this, one should ensure that when designing workstations including handheld loads, such as tools, that the task is focused in the normal work area in front of the trunk.

All of the above evidence shows that when designing or creating accommodations for someone with a RCT, moving tasks in front of the person and below shoulder height improves their ability to complete a task with minimal pain. This region shrinks when handheld weight is added with an extended reach, so larger items should be kept low. Handheld weight itself did not have as great an impact with larger cohorts as with pilot work, particularly in the pared down data.

The differences between groups were expected, however the group order of reach lengths was not. It was expected that the young asymptomatic cohort would have the longest reach through each of the 3 load conditions. It was casually observed by researchers that the young asymptomatic group was the most vocal about the challenges of the handheld weight trials, whereas the age matched asymptomatic and symptomatic groups were stoic. It became apparent with the symptomatic participants that they may not ask to stop testing if they felt pain, so researchers began watching for facial cues. This observation is outside of the scope of this project, but was interesting to observe.

Future work will include more recruiting more participants, with the hopes that more data can allow for more information to be found. For instance, it was observed that different symptomatic persons chose different strategies for how they performed reach trials. There may be some sort of pattern that could be identified based on which of the 4 RC muscles is injured, or if different types of repairs recover reach in different regions.

Chapter 4.0 Knowledge Translation

4.1 Knowledge Translation

Creating tools to disseminate results in meaningful ways to all stakeholders in research is one of the biggest challenges researchers currently face. The stakeholders in this particular project include the researchers, participants, orthopedic surgeon and other health care providers such as physiotherapists, rehabilitation specialists, occupational therapists and potentially even those making return to work decisions (Azimi et al. 2015; Graham et al., 2006). One of the major barriers to successfully sharing of findings with others can be specialized technical jargon, and for this study in particular there is a certain complexity in the mathematical components of different coordinate systems.

From discussions with the clinicians ; spherical coordinates were easier to visualize as the origin is at the acromion, with the reach lengths in respect to angles being more intuitive than the projections used in cylindrical coordinates. It was also thought that diagrams or images can be more self-explanatory, so the focus was put on creating these, and using the spherical coordinate data. The percentile curves presented in Figure 10 mimic where the reach and work space literature start (Das et al., 1994; Farley, 1955; Faulkner & Day, 1970; Konz & Goel, 1969; Stoudt, 1973). They differ somewhat from previous, in that they are presented with the reach length normalized to participant arm length which allows for easier extrapolation for design needs. These curves are also with respect to the acromion as opposed to table height but could be translated for this purpose. It is known that ROM and reach tend to be smaller when seated, so using these curves as outer design parameters for a potential workspace or creating accommodations for activities of daily living tasks will ensure that symptomatic participants are put at minimal risk of further injury.

To compare a particular symptomatic participant's reach to their cohort and to compare to asymptomatic reach was thought to be a key to both participant retention, as well as a way to communicate back to clinicians where their MRE was lacking. Similar to how a globe can be flattened to create a map of the world, the binned MRE was flattened to create reach maps. Regions where everyone can reach and areas where people struggle can be identified at a glance. Participants who have come for follow-up testing have given good feedback on these maps, and have found them easier to understand than just the overlay of their MRE of different visits. It was easier to see the changes that happen, and also gives a benchmark to see how the rehabilitation of the shoulder is going.

4.2 Knowledge Translation Results

Percentile curves for the reach of 5^{th}, 50^{th} and 95^{th} percentiles for each group were created from the reach length vectors, to compare to previous curves. These values were pulled from the +/- 100mm bands on either side of the acromion. Averages for each of the participants was taken in each of the 8 theta bands (Theta 1 $>-75^{o}$ was removed due to missing data points), then an overall group average was created. For the symptomatic group, bins between -60^{o} and -30^{o} were removed due to the small number of participants who could reach in these regions.

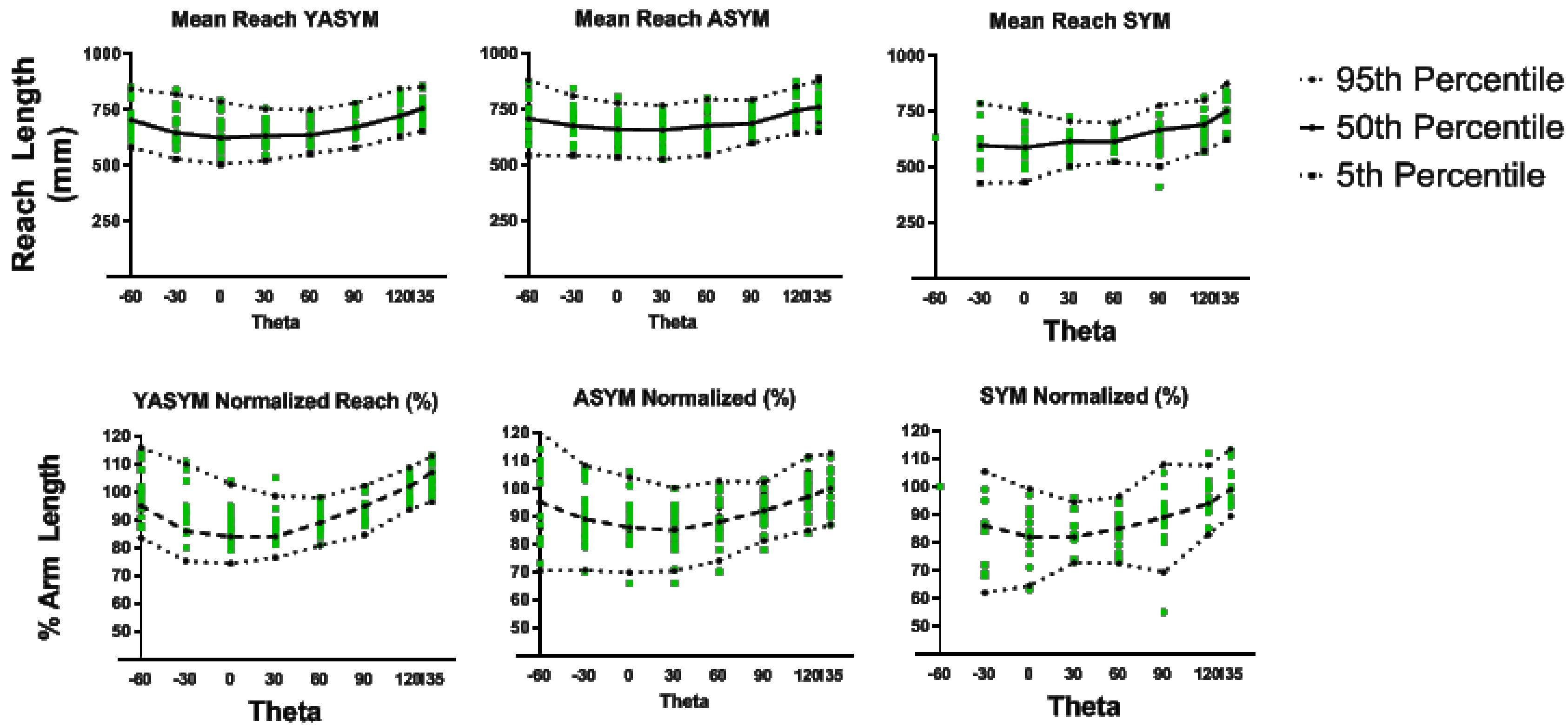


Figure 10: Percentile Reach Curves for 3 Groups

To make these overall differences easier to interpret, and more practical for use by clinicians and participants, maps of where participants could reach were created. In regions where all participants could reach (such as the center of the age matched group), the space is lighter, with darker regions indicating where fewer could reach. This percentage was done for each group to reflect different sample sizes. These were only done for the spherical coordinate systems, as it was more intuitive for clinicians and participants to understand. There are small changes to where participants could reach with the added handheld loads, as can be seen in Table 14, Table 15 and Table 16.

Table 14: Participant Reach with 0.0 kg Load

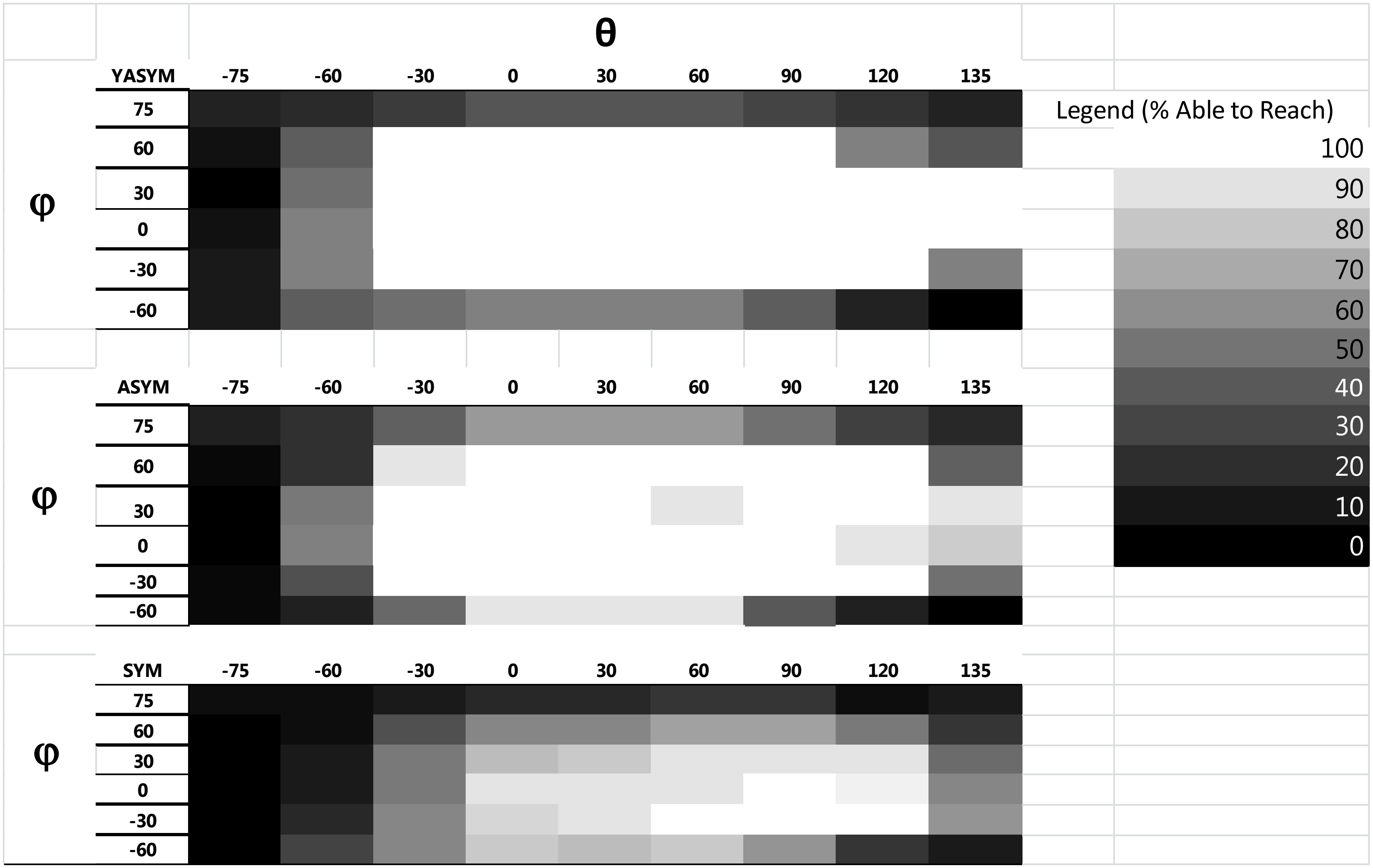


Table 15: Participant Reach with 0.5 kg Load

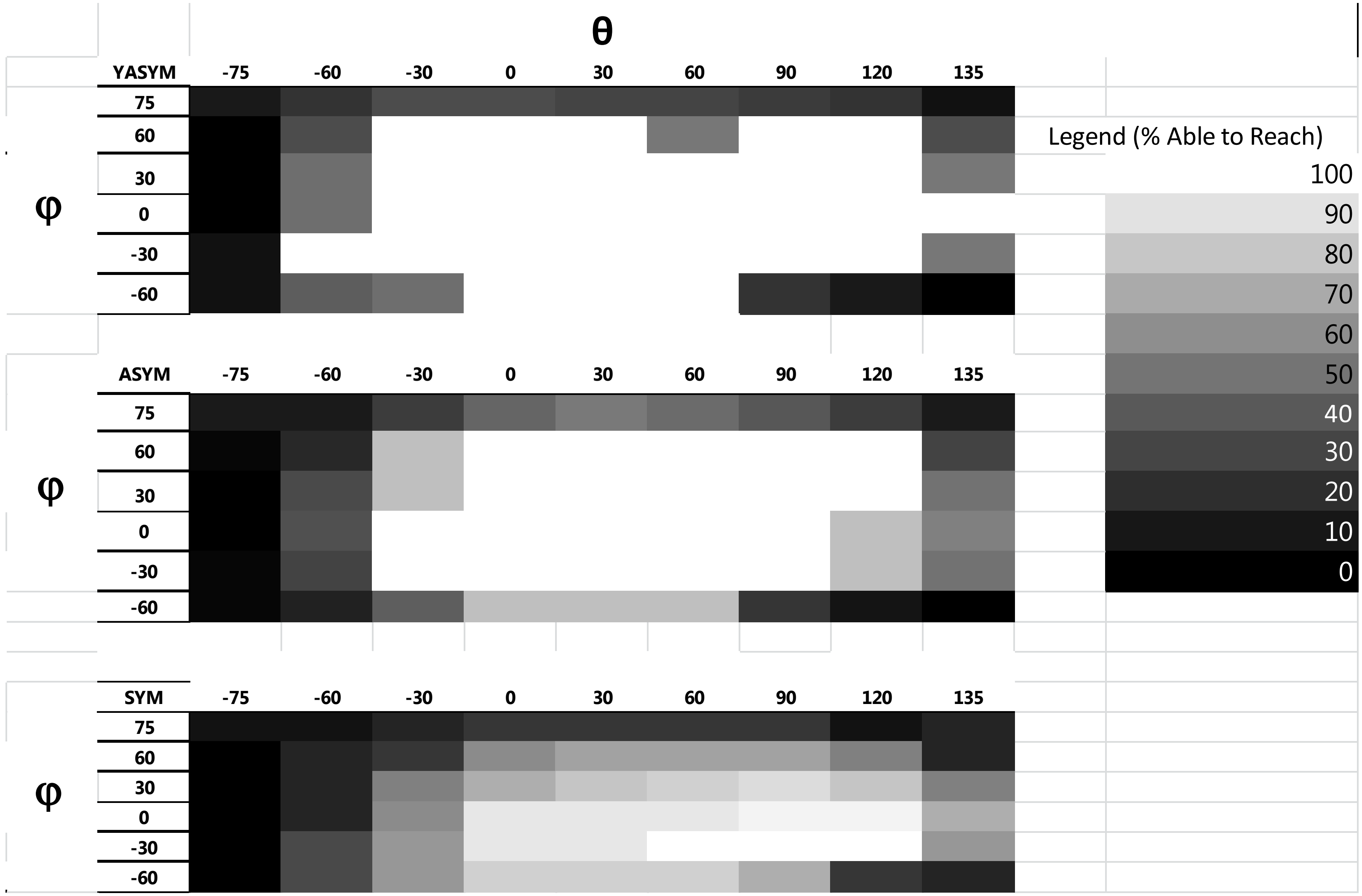
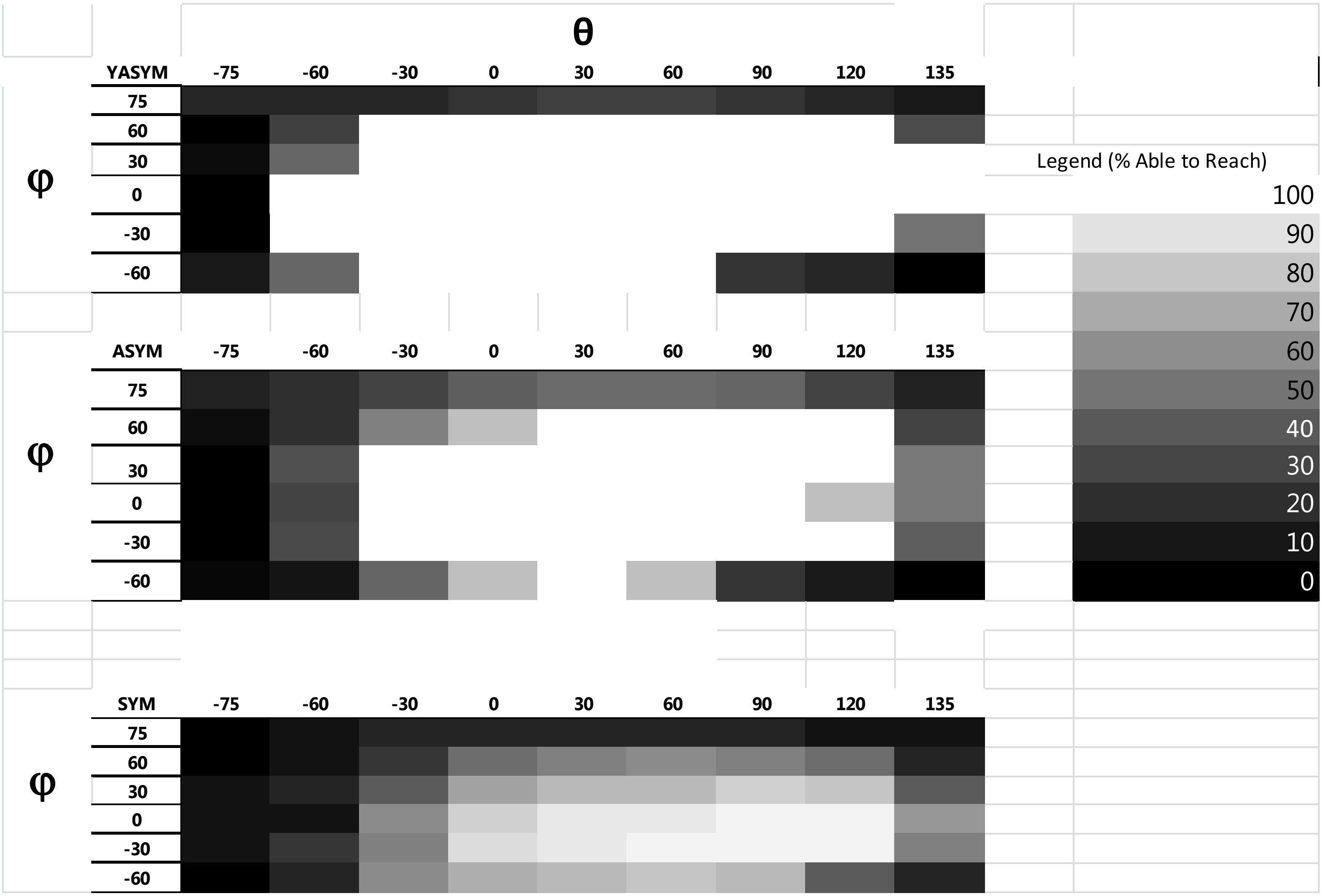


Table 16: Participant Reach with 1.0 kg Load



4.3 Knowledge Translation Discussion

The reach maps are able to clearly show that reach above 75°, more than -60° behind the shoulder, and more than 135° across the body are regions in which all persons struggle. These are regions of peripheral maximum reach for most, which make them risky regions to in which to perform work. The literature has always been a proponent of keeping tasks in front of the body, and central when possible, and these plots give further validation to this point (Choi & Mark, 2004; Konz & Goel, 1969; Stoudt, 1973). For symptomatic participants, this central region becomes smaller, with shoulder height or just above being the highest reach. This region becomes even smaller as handheld weight is added, and really highlights the need for accommodations to allow persons with RCTs to continue with their activities of daily living. The tested symptomatic cohort was 73% right shoulder, meaning many are dealing with impairment in their dominant arm and using the left may take some practice and training. Potentially, there is a need for an ergonomic assessment to help make accommodations suggestions or assist with dexterity training on the non-dominant arm for reaching tasks to allow persons with RCTs to maintain their quality of life while waiting for repair.

It is hoped that as more participants come in for follow-up, and as the cohorts grow, these reach maps can become an automated report created and sent to track progress and maintain motivation within participants. It can be easy to lose sight of progress and improvements happening during the recovery period. Future work on knowledge translation tools will include a way to extend past where a participant can reach as a binary yes or no for a region, into how far can they reach. Several methods were tested, with the results lacking clarity and a direct message that is meaningful to clinicians or participants.

Chapter 5.0 Measurement of Reach Kinematics

5.1 Introduction

This chapter will review the functional anatomy of the shoulder complex as well as the specific musculo-skeletal disorder called rotator cuff tears (RCT) that are the focus of this research. Lastly the chapter will present a new method of assessing the shoulder/reach kinematics using a principal component analysis.

5.1.1 Anatomy of the Shoulder

The shoulder, or glenohumeral joint, is one of the most mobile joints in the body; however it sacrifices joint stability for mobility (*Rotator Cuff Tutorial.* 2011). This means the shoulder is not a highly stable joint, and is susceptible to injury. Skeletally, the joint is described as a synovial ball and socket joint where the large humeral head rests in the shallow glenoid cavity of the scapula. There are several palpable, bony landmarks surrounding the glenohumeral joint namely the acromion, and the coracoid process. There are also many connecting tendons and large muscles (Saladin 2007, Shoulder Joint Tutorial. 2012). A diagram of the anatomical structures of the shoulder is presented in Figure 11: Anatomy of Glenohumeral Joint It is important to note that motion of the joint includes the articular surfaces and the scapula itself. This makes determining the instantaneous joint center challenging, adding to the complexity of modelling the shoulder.

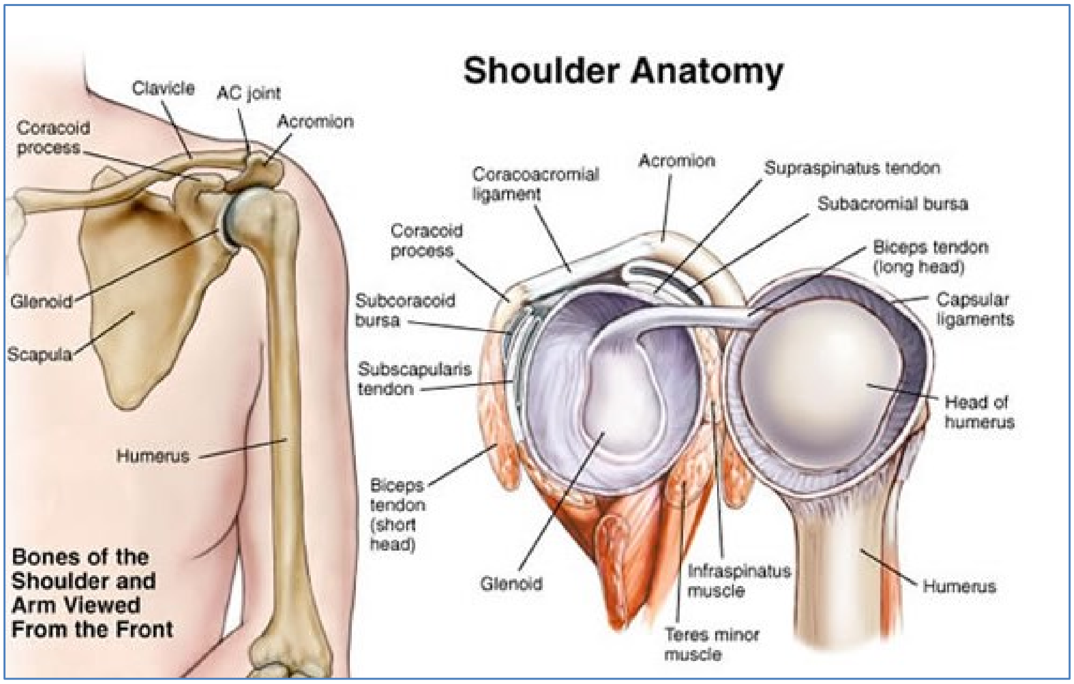


Figure 11: Anatomy of Glenohumeral Joint

5.1.2 The Rotator Cuff

Some stability of the joint is achieved by the array of ligamentous tissue that surrounds the joint and also forms the joint capsule (Figure 1). However, it is generally thought that the primary source of joint stability is achieved by the surrounding musculature. Collectively, the muscles which surround the joint are called the rotator cuff. This group of muscles and tendons in the shoulder maintain the connection of the humerus to the scapula, where the muscular forces transmitted through tendons provide stability and allow movement. The rotator cuff is comprised of 4 muscles: subscapularis, supraspinatus, infraspinatus and teres minor. The supraspinatus lies over top of the scapula and inserts at the top of the greater tuberosity of the humerus. In general, this muscle serves to abduct the humerus. The infraspinatus lies below the scapula and inserts at the posterior facet of the greater tuberosity. The action of this muscle is to externally rotate the humerus. The teres minor runs between the middle half of the lower scapula, and inserts below the infraspinatus on the greater tuberosity, again assisting in externally rotating the humerus. The subscapularis runs along the underside of the scapula to insert in the lesser tuberosity of the humerus, internally rotating the humerus (Saladin 2007). A diagram showing these muscles in the anterior and posterior view of the left shoulder can be seen in Figure 2.

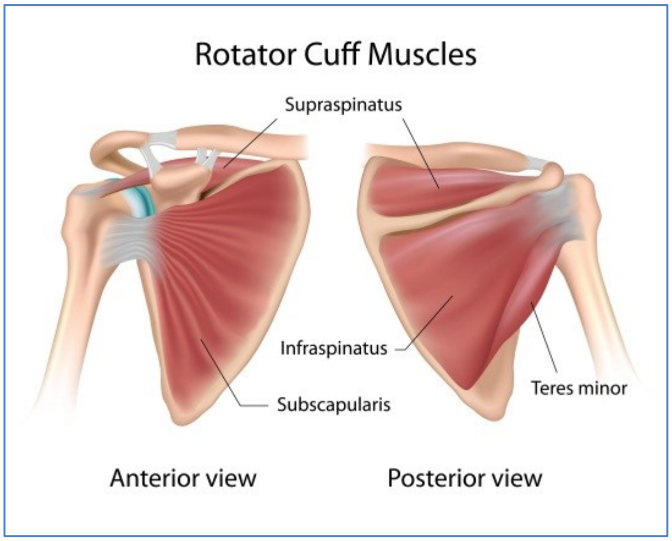


Figure 12: Muscles of the Rotator Cuff (retrieved from http://www.shouldercommunity.com/wp-content/uploads/2012/07/anatomy_rotator-cuff-muscles-2.jpg, 2016)

There are many conditions that can affect the functional capability of the shoulder joint such as tendonitis, impingement of the tendons, frozen shoulder, sub-acromial bursitis and of course partial or total rotator cuff tears. Many of these injuries are gradual, and tend to be due to repetitive motions.

5.1.3 Rotator Cuff Injuries – Surgery

Rotator cuff injuries can happen either gradually, through a series of degenerative tears and repetitive strains, or be instantaneous as a result of traumatic impact such as a fall or lifting heavy weight. Persons at risk for rotator cuff injuries tend to perform a lot of overhead motions in their daily lives, such as painters, carpenters, baseball or tennis players as well as persons who experience chronic shoulder dislocations. Partial thickness tears may recover in time given proper rest and physical therapy, however full thickness tears or chronic partial tears may require surgery. Some of the symptoms of a rotator cuff injury include pain in the arm or shoulder area particularly when trying to sleep on the injured shoulder, weakness or tenderness in the shoulder, difficulty moving the shoulder- particularly if trying to reach overhead. If a traumatic event occurs where a rotator cuff tear is suspected, one should seek medical assistance as soon as possible (Mayo Clinic Staff 2016).

Rotator cuff tears (RCT) are the most common shoulder disorder accounting for 7-40% of all shoulder issues, and become more prevalent in older populations (Neviaser et al. 2012). There are several factors that must be examined to classify a RCT (Jaeger et al. 2014) beyond whether a tear is full or partial thickness.

- Tendons affected
- Tear localization
- Tear size
- Retraction of tendons
- Degeneration of muscles

Most full thickness tears involve the superior and posterior rotator cuff, and the Ellman, Bateman or Patte classifications are the most commonly used. Several tools can be helpful in classifying tears. Conventional x-rays don't allow for visuals of the tendons or muscles but help with ruling out complicating factors such as arthritis, or movement of the humeral head. Ultrasounds are useful as they are readily accessible and have good sensitivity for showing the size of a tear. Magnetic Resonance Imaging (MRI) is the gold standard of tests as it gives a full visual of the affected area, helping to fully classify the tear and decide on the best course of treatment (Jaeger, Izadpanah et al. 2014). Patients presenting with moderate symptoms can typically be managed without surgery for a period of several years, however they must be followed to ensure that there is no structural degeneration in this time as this may later impact the efficacy of surgery. One method used to compare mobility pre and post-surgery is the Constant Score, shown in Table 17: Constant Functional Scoring Table. This score compares the injured and uninjured side using range of motion, pain indicators and strength measures. The score can be useful to quantify patient improvements following RCT repair (Gazielly et al. 1994).

Table 17: Constant Functional Scoring Table

		Right Shoulder	Left Shoulder
Subjective 35 points/ 100	**Pain:** 15 points/ 100 None 15 Mild 10 Moderate 5 Severe 0		
	Activities of Daily living: 20 points/ 100 Professional handicap (0 to 4 points) 0: severe handicap, 4 points: full work Recreational handicap (0 to 4 points) Sleep (0 to 2 points) Affected sleep: 0 points, unaffected sleep : 2 points Level of use of hands (10 points)		

	Waist Ziphoid Neck Top of Head About Head 2 points 4 points 6 points 8 points 10points		
	Subtotal/ 35 points		
Objective 65 points/ 100	Painless active mobility: 40 points/ 100 Forward Elevation 0-30 / 30-60 / 60-90 / 90-120 / 120-150 / 150-180 0points 2points 4points 6points 8points 10points Lateral Elevation 0-30 / 30-60 / 60-90 / 90-120 / 120-150 / 150-180 0points 2points 4points 6points 8points 10points External Rotation Hand behind head with elbow held forward 2 points Hand behind head with elbow back 2points Hand on top of head with elbow held forward 2points Hand on top of head with elbow held back 2points Full elevation from top of head 2points Internal rotation: Dorsum of hand to Thigh Buttock Sacrum L3 Th12 Th7 0point 2points 4points 6points 8points 10points		
	Power 25 points/ 100 Measured in 90^{o} abduction in scapula plane using a dynamometer		
	Subtotal/ 65 points		
	Total/ 100 points		

Following surgery, the arm is typically placed on an abduction cushion and braced for 6 weeks and only guided movement by a physiotherapist should be done during this time.

After 6 weeks supervision of recovery by a physiotherapist, and range of motion will be limited slightly until 8 weeks. Table 18: Postoperative rehabilitation timeline after rotator cuff repair shows a timeline for postoperative rehabilitation (Jaeger, 2014).

Table 18: Postoperative rehabilitation timeline after rotator cuff repair

	1p.o. day. Week 1-3	Week 4-6	After 6 weeks	After 8 Weeks
Brace	15^{o} Shoulder Abduction Brace		None	None
Physiotherapy/ CPM	Straining of the shoulder muscles Oscillation according to Maitland (Detonization of the capsule) Glenohumeral centering			
Range of Motion	No active glenohumeral motion	Active moderate Flexion/Extension Slight internal and external rotation	Free No limitations for abduction and adduction	Free Strengthening of abduction and adduction
Training	Training of the forearm Training of the contralateral arm		Abduction 90^{o} Adduction 90^{o} External rotation up to 0^{o} Internal rotation up to 0^{o}	Training of coordination and 3D motion Increasing of power Isokinetic training of the internal and external rotation

There is always a chance of re-injury or tear of the rotator cuff, and is dependent on many factors; patient's age, extent of the tear, fatty degeneration of the rotator cuff muscles and bone mineral density. Long term outcomes post-surgery strives to decrease the pain and increase the functionality of the shoulder through improving strength and range of motion. The Constant Functional score is one method to gage improvement, and Gazielly et al found that 84% recovered 90% of their mobility, although some still had reduced capabilities to perform activities of daily living, particularly as muscular strength was decreased in 80% of repairs. It was found that pre-operative exercise or rehabilitation program helped with stiffness and a patient's ability to regain their active mobility post-surgery, although those with chronic recurring defects did not have as much improvement (Gazielly, Gleyze et al. 1994). These results tend to be seen regardless of the size of the tear, although the most marked improvements in range of motion tend to come from those with repairs of larger tears. Most patients were able to return to work or their routine overhead activities after 3.7-4.2 months of recovery (Burkhart et al. 2001).

5.1.4 Principal Component Analysis

PCA is an eigenvector-based multivariate statistical procedure that utilizes orthogonal transformations of large data sets that may be correlated into components that are linearly uncorrelated. These individual components are called "principal components" (PCs) with each subsequent component accounting for less variability than the previous (Shlens, 2014). PCA is a straightforward method to extract the most relevant pieces of information from large, multidimensional sets, and helps find a meaningful method to express a data set while reducing noise or redundancy in variables. Most currently available statistical analysis programs have built in functions for PCA.

PCA has become widely used in many fields of empirical science; and has been shown to be effective in an array of human motions such as analysis of gait kinematics (Deluzio & Astephen, 2007), as well as kinetic and EMG patterns related to human motion (Butler et al, 2009). As an example, Deluzio and Astephen (2007) utilized the full gait cycle waveform (displacement – time series) as a PCA input as opposed to just a single specific parameter such as a peak angle or moment as used in other types of comparisons. They argued that this provided a more objective comparison between subject groups as speculation on what is an atypical waveform compared to a single discreet value.

Deluzio and Astephen (2007) found that the first 3 principal components (PCs) for the flexion angle, flexion moment and adduction moment accounted for over 90% of the variance in each characteristic. From these 3 key features, the major differences between the groups were able to be parsed out using the high/low values of the waveform within each PC. From the PCA, statistical tests such as ANOVA can be used to test PC scores for differences among groups or other experimental treatments, giving researchers another way to highlight differences in large, complex data sets.

One of the observations made about individuals with shoulder impairments is a reduction in “reaching ability”. This can refer to reach distance as well as reach angles (similar but not identical to joint range of motion). The objective for this section was to apply the methods of PCA to the multi-dimensional, angular reach data and to evaluate the use of PCA as a data reduction method for maximum reach envelope data. As an initial attempt, the PCA was applied to the maximal phi angles across a range of theta values in spherical coordinate data extracted from the MRE. This process gives a way to reduce the dimensionality of the data to allow for statistical comparisons to find main effects of group and load on the maximum reach angle in each theta band of the MRE.

5.2 Methods

The MRE data for each participant was sorted into the 9 theta bands (in spherical coordinate systems, Figure 13) and from these, the three greatest phi angles within each theta band were extracted. Three values were selected to provide a generalize measure of the maximum phi position to reduce the impact of singular values that could be affected by noise or measurement artifact. It was noted that theta band 1 (>-75^{o}) had too many values missing, so this band was not used in the analysis. This left 8 theta bands with (typically) 3 values per band for each experimental condition for each participant. All values from each participant for the 3 groups (young asymptomatic, age matched asymptomatic and symptomatic) were merged to form one large file. In cases where there were fewer than 3 values in a theta band, all available values were utilized.

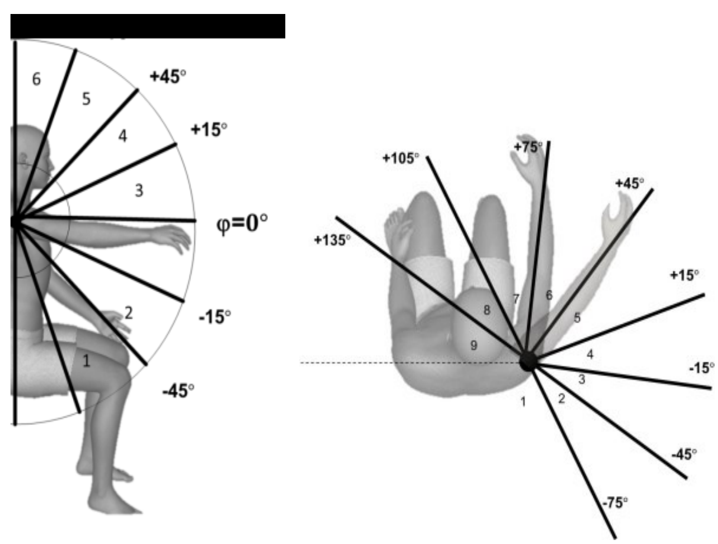


Figure 13: Spherical coordinate divisions

The master datasheet was created and imported into Minitab 18. Graphs of the outputs were created using Graph Pad Prism 8. The PCA was first performed on each of the 3 load conditions separately, and then with all 3 load conditions together. Following the creation of the PC the PC scores were used to test for difference among the three groups across the reach profile and the load independently ad in combination.

5.3 Results

In all cases, the first 3 PCs accounted for more than 95% of the variance. The individual plots of the maximum phi angle for each participant can be seen in the top row of Figure 14. The middle plots of Figure 14 show the group mean phi angle, with the PC scores in the bottom row of the plot. In each of the plots the symptomatic group had lower mean reach angles (middle row), with the two asymptomatic cohort's being reasonable similar.

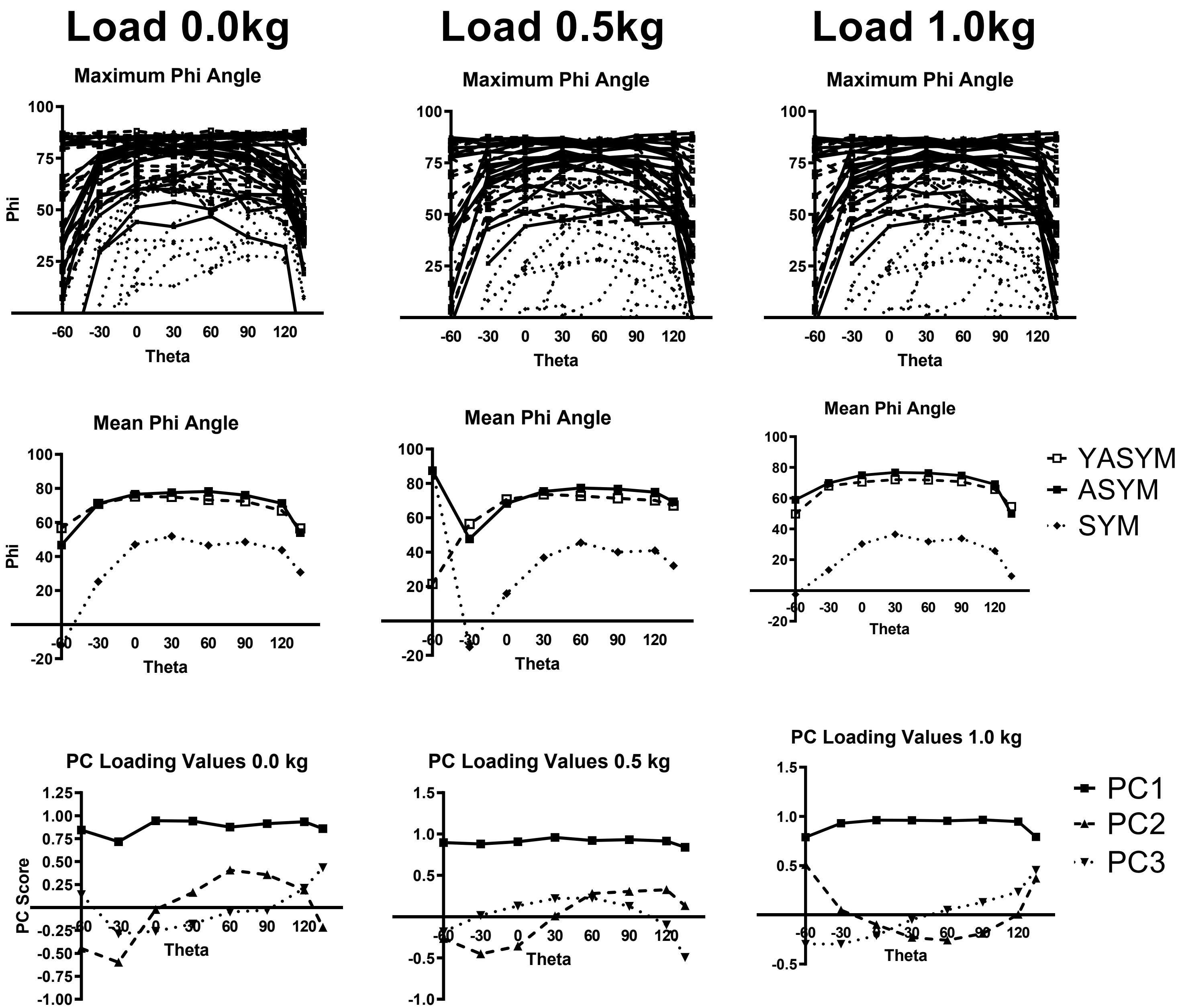


Figure 14: PCA results for individual loading conditions

It is possible to use the PC scores to test for differences in the reach pattern associated with each PC. In this case three independent, one-way ANOVA's were performed on data within each load condition. In all three cases there were differences in the main effect of group ($F= 3.05$, $df =2$, $p<0.52$; $F=16.90$, $df =2$, $p<0.05$; $F=2.99$, $df =2$, $p<0.055$) for the 0.0, 0.5 and 1.0 Kg load conditions respectively. Tukey's pairwise comparisons were completed for all three analyses and presented in Table 19 is a summary of the results of this analysis. Groups that share the same letter did not differ from each other.

Table 19: Tukey post-hoc ANOVA groupings

Load	Group	PC1	PC2	PC3
	YASYM	A	A	A
0.0 Kg	ASYM	A	B	B
	SYM	B	C	A, B
	YASYM	A	B	B
0.5 Kg	ASYM	A	B	A
	SYM	B	A	A
	YASYM	A	A	B
1.0 Kg	ASYM	A	A, B	A, B
	SYM	B	B	A

For all 3 load conditions, PC1 shows no difference between the young and age-matched asymptomatic groups but both groups differ from the symptomatic group. PC1 represents the magnitude of the mean phi angle for each group. PCs 2 and 3 are more complex and change as handheld weight is added.

With no load, PC 2 scores show differences among the 3 groups. When 0.5 kg is added, the two asymptomatic groups are the same and both differ from the symptomatic group. Lastly, when holding 1.0 kg the difference was between the young asymptomatic and the symptomatic group with the age matched asymptomatic group being similar to both.

Differences in PC 3 scores across the loads were also found with different effects based on the actual load. With no load and 1.0 kg the young asymptomatic and symptomatic groups are similar, as are the age matched asymptomatic and the symptomatic. With 0.5 kg, the two age-matched populations differ from the young asymptomatic group. These differences may be related to an age factor alone and independent of injury status.

These analyses can only examine the effect of group, but not the impact of load, hence the need to put all 3 load conditions into one analysis. When looking at the overall PCA, considerations for load and group need to be made at the same time, so a mixed effect model was created to test for differences. In Figure 15, there appear to be patterns in the scatter plot of the first two PCs with the symptomatic group being more negative in PC1. The two asymptomatic groups both are clustered closer to the origin.

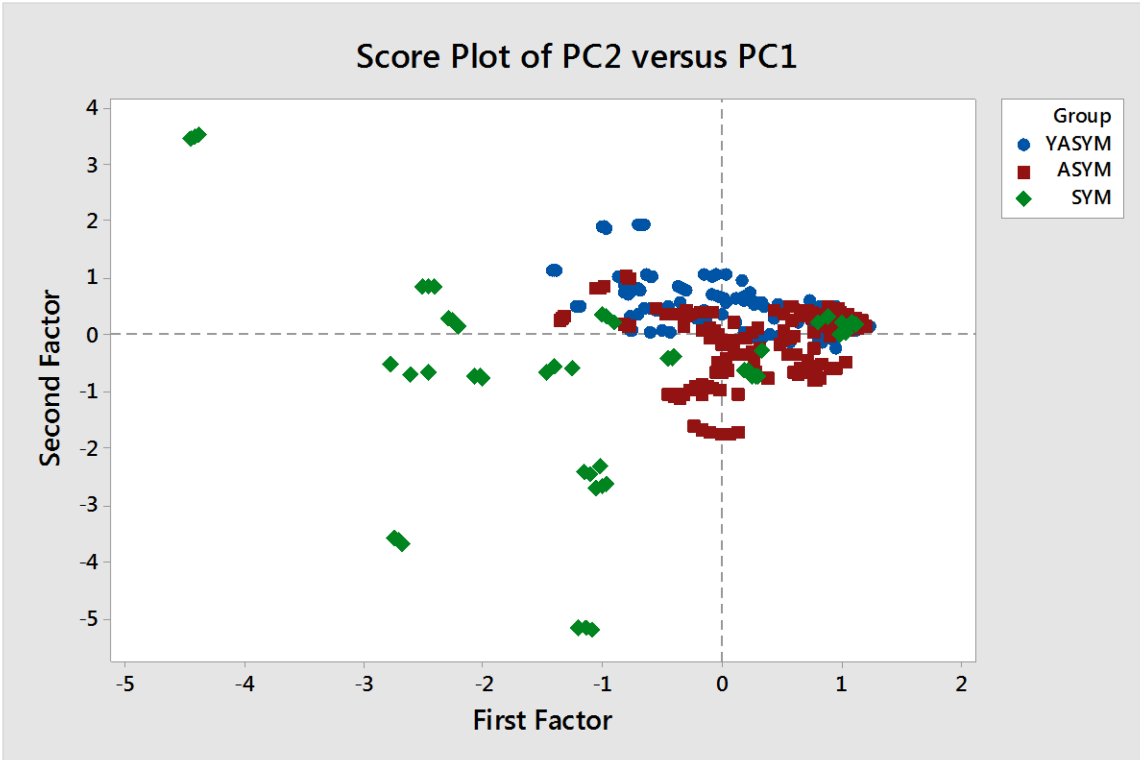


Figure 15: Score plot of PC2 vs PC1

When looking at a plot of the PC loading output, Figure 16, it can be seen that again PC1 is positive and close to 1, with PCs 2 and 3 starting positive, becoming negative, and then increasing. PC1 still summarizes the magnitude of the mean reach angle, with PCs 2 and 3 accounting for the differences between group and load performances.

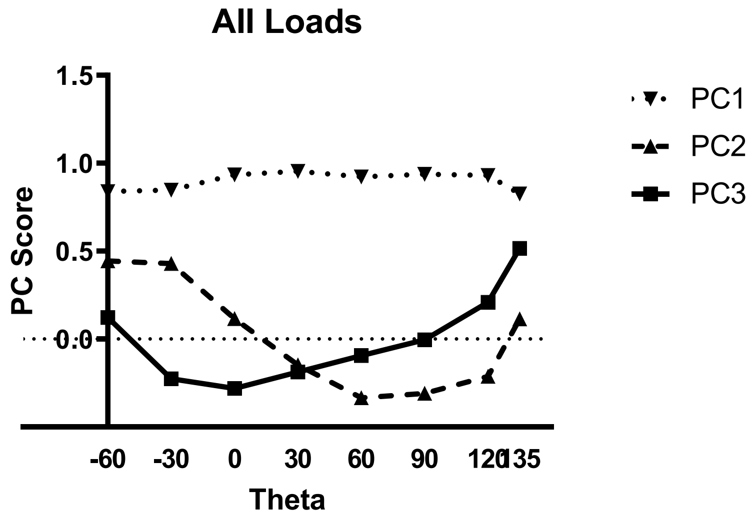


Figure 16: PCs for 3 load analysis

Post-hoc comparisons of the PCs for the individual load and group values can be seen in

Table 20. With regards to the load portion, PC1 shows differences between the no load and loaded condition, PCs 2 and 3 find that there are similarities between the 0.0 kg and 0.5 kg conditions, and between the two loaded conditions, but not between the no load and 1.0 kg conditions. In terms of group differences, PC1 shows differences between the symptomatic and asymptomatic groups (both), PC2 differentiates between the young asymptomatic and symptomatic group, but the age matched asymptomatic can be compared to either of these. PC3 found no differences between the groups.

Table 20: Tukey post-hoc comparisons by group and load independantly

		PC1	PC2	PC3
Load	0.0 Kg	A	B	B
	0.5 Kg	B	A, B	A, B
	1.0 Kg	B	A	A
Group	YASYM	A	A	A
	ASYM	A	A, B	A
	SYM	B	B	A

Looking at the interaction between load and group, the output becomes more complex. From PC1, all group by load interactions were the same with the symptomatic cohort differing with any handheld load. PC2 again has 2 distinct interactions; the first showing similarities between every combination except symptomatic no load, and age matched asymptomatic being similar to the symptomatic tests. PC3 shows no differences between the conditions.

Table 21: Tukey post-hoc comparisons of group by load interactions

PC1		PC2		PC3	
Group*Load	Grouping	Group*Load	Grouping	Group*Load	Grouping
ASYM 0.0 kg	A	1 0.5 kg	A	3 1.0 KG	A
ASYM 1.0 kg	A	1 0.0 kg	A	1 1.0 KG	A
ASYM 0.5 kg	A	1 1.0 kg	A	3 0.5 KG	A
YASYM 0.0 kg	A	2 1.0 KG	A B	1 0.0 KG	A
YASYM 0.5 kg	A	2 0.5 KG	A B	1 0.5 KG	A
YASYM 1.0 kg	A	2 0.0 KG	A B	3 0.0 KG	A
SYM 0.0 kg	A	3 1.0 KG	A B	2 0.0 KG	A
SYM 0.5 kg	B	3 0.5 KG	A B	2 1.0 KG	A
SYM 1.0 kg	B	3 0.0 KG	B	2 0.5 KG	A

5.4 Discussion

PCA has been shown to be a powerful tool that can help quantify differences in large and complex data sets in a variety of human motion activities, in particular with multidimensional data such as time series or other forms where meaningful information lies in the patterns as opposed to discrete variables. In this study this statistical tool was used to test the effects of load and group on one measure of human reach extract from the MRE. Using the maximum phi angle at different theta angles (horizontal angles) gives a snapshot of the range of motion capabilities of a participant during a dynamic reaching trial, and moving to a unit-less method of data reduction, can find differences. Focus was on the maximum reach angle as all of the participants had similar minimums. All participants could reach a good portion of the lower angles, differentiation happened when the symptomatic participants had to start lifting the arm.

In the individual PCAs by load, the principal components could start to be attributed to particular features of the data set. PC1 represents the magnitude of the reach angle, which was expected based on outputs from other analysis (Deluzio & Astephen, 2007) and practice data sets. Defining PCs 2 and 3 is a little more complex, but they seem to be teasing out the differences between the reach patterns of the particular group. PC2 has a similar shape for the 0.0 kg and 0.5 kg models where it starts negative, becomes positive between 0^{o} and 30^{o}, increases then finishes negative. For 1.0 kg PC2 starts positive, then curves to lowest negative at 60^{o} then curves back up. PC3 also has a complex shape that changes with the addition of load.

The overall analysis is more complex and harder to infer what PCs 2 and 3 are signifying.

PC1 shows the same high mean as previously, meaning that it represents the magnitude of the reach angle. The post hoc analysis showed the interaction of group by load really highlights that many of the symptomatic participants did struggle with the loaded condition.

Moving forward, there are options and choices to be weighed as to the need for keeping the analyses simple to allow for less complex interpretations. Future work for this piece of the project will include continuing to compare the maximum reach “waveform” and the PCA with respect to some of the other variables collected to see if they can be added in the analysis.

Chapter 6.0 Post Surgical Repair Changes to MRE: Case Studies

6.1 Introduction

Immediately following RCT surgical repair, the affected shoulder is immobilized using slings for several weeks while doing physiotherapy and recovering. The sling is removed approximately 6-8 weeks following surgery and slight motion started under the supervision of the physiotherapist. Arm movement is limited in this time, and large reaching movements are minimized, or performed with the opposite arm.

The Nova Scotia Worker's Compensation Board aims to follow the American Academy of Orthopedic Surgeon`s position statement on early return to work following injury where possible, and has developed guidelines for rotator cuff tears (Table 22) (*Safe and timely RTW is in the best interests of patients, to improve quality of life for the injured worker,* 2000; Workers' Compensation Board of Nova Scotia, 2016). There is no differentiation between cases where there is a full or partial tear, or if surgery is required. The guidelines reflect the goals of balancing mental and physical well-being of injured persons, and are one piece in the multidisciplinary approach to recovery after acute injuries.

Table 22: Return to work guidelines for RCTs

Rotator Cuff Tear

Job Classification	RTW Minimum/Maximum
Sedentary Work	0 days – 4 days
Light Work	0 days – 1 week
Medium Work	2 week – 6 weeks
Heavy Work	4 weeks – 12 weeks
Very Heavy Work	4 weeks – 12 weeks

The initial intention of this research was to collect CPSAM MRE and ROM data pre-surgery and at 3, 6, 12 and 24 months post-surgery. Due to a number of scheduling conflicts, there was a lack of participant retention for these follow-ups. Only two participants were able to be followed post-surgery at the time of this document. SYM003 was tested 12 months post operation, and SYM017 was tested 3 months post operation. The objective of these post-operative measures was to document how reach, range of motion and strength changes during post-surgical recovery and evaluate the efficacy of the above dates with regards to a person's functional capability. Given the low number of follow-ups the remainder of this chapter will focus on a qualitative assessment of the observations and measures made on these two participants. When and where possible, comments will be provided to assist future work related to participant follow-up post- surgery.

6.2 Methods

At the beginning of the study, it was agreed that for 3 and 6 month testing, no handheld weights would be used to allow time for full recovery of the soft tissue (muscle) acting about the shoulder joint. The MRE procedure would follow the test protocol as before, with only the zero load condition being tested. At the 12 and 24 month testing the MRE testing would follow the initial protocol with hand-held loads (Johnston et al., 2016).

Statistical analysis was done by creating 54 bins across the volume, as previously described; however comparisons are to initial participant pre-operative collections as opposed to the group means.

6.3 Results

6.3.1 Month Post Operation (SYM017)

When comparing SYM017s MRE pre and 3months post-surgery, the biggest differences were seen in the region behind the shoulder. This can be seen in Figure 17 where white indicates regions where the subject reached. Observable improvements are noted in the -75° to -30°, and 90° theta bands, particularly in middle phi bands.

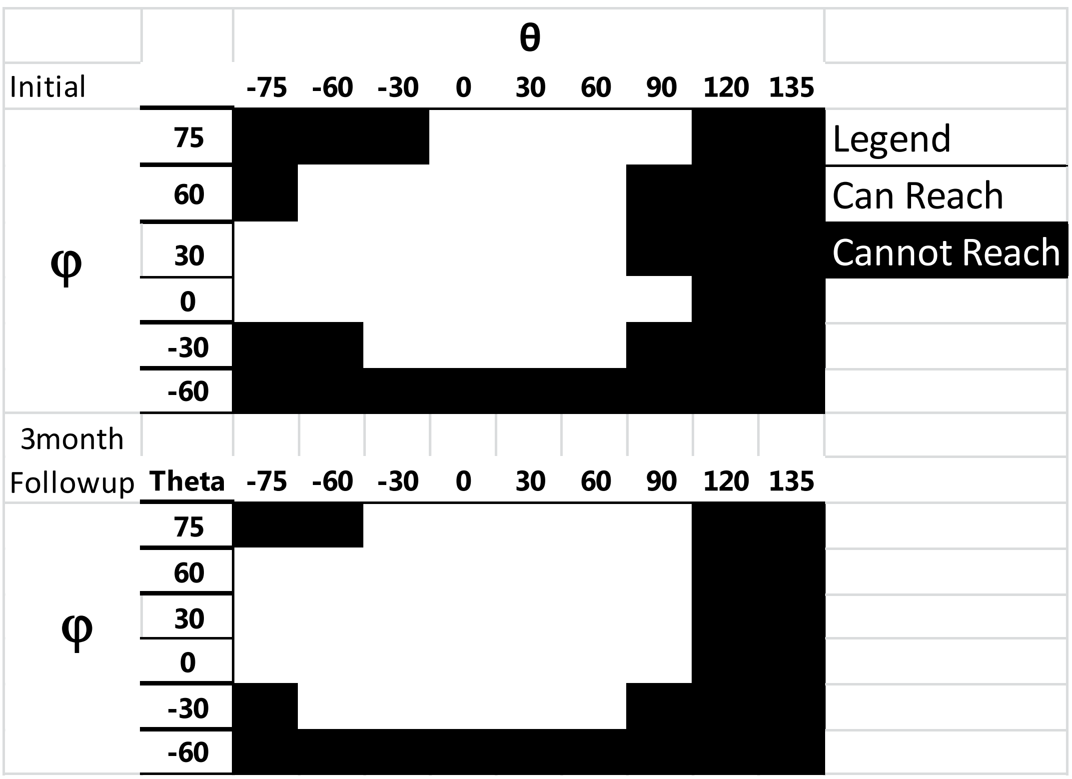


Figure 17: SYM017 MREs pre and 3 months post-surgery

Table 23 shows significant differences in the overall mean reach values between visits for the no load condition. In the theta (horizontal) bands 3 main effects were found. One effect includes all bands except 8 and 9 (>105°) having the smaller mean values, followed by bands 1,3,4,5, and 8 creating the middle mean group with bands 1,4,5,8 and 9 in the higher mean values. There are 2 main effects found in the phi (vertical) bands with the bands near the bottom of the envelope (1-3) having higher mean reach values than bands 1, 4 and 5. The highest band (above 75^{o}), did not have reach values for either visit.

Table 23: Descriptive statistics for reach of SYM017 pre and 3 months post-surgery

Period	N	$N_{missing}$	Mean (mm)	StDev (mm)	Minimum (mm)	Maximum (mm)
Initial	26	28	728	58	648	850
3 Month	31	23	696	54	617	804

With respect to range of motion, changes occur with the largest between active flexion, CPSAM abduction and passive abduction, but these changes do vary in direction (Figure 18).

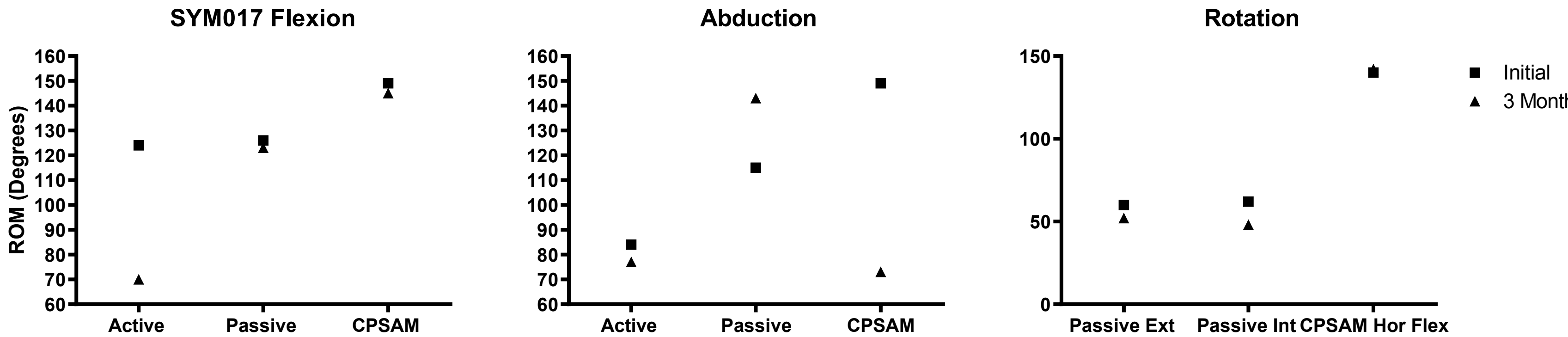


Figure 18: SYM017 ROM measures pre- and 3 months post-surgery

Strength measures also vary between assessments (Figure 19) with abduction and internal rotation improving, and external rotation decreasing.

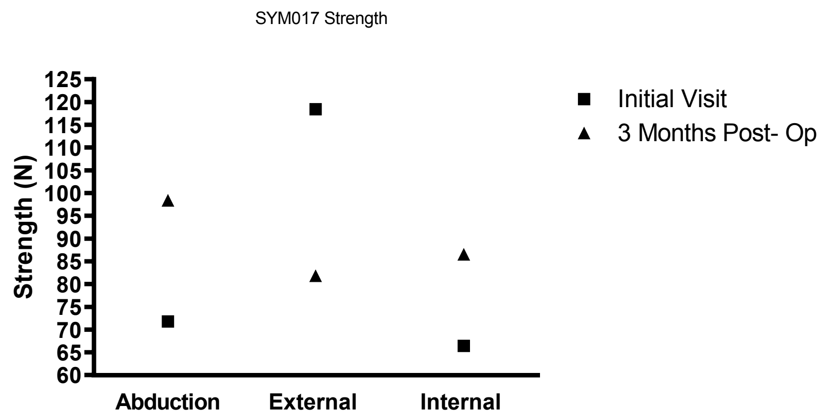


Figure 19: Strength measures for SYM017

6.3.2 12 Months Post Operation (SYM003)

With respect to SYM003s 12 month follow-up, the biggest differences are seen above shoulder height (Figure 20).

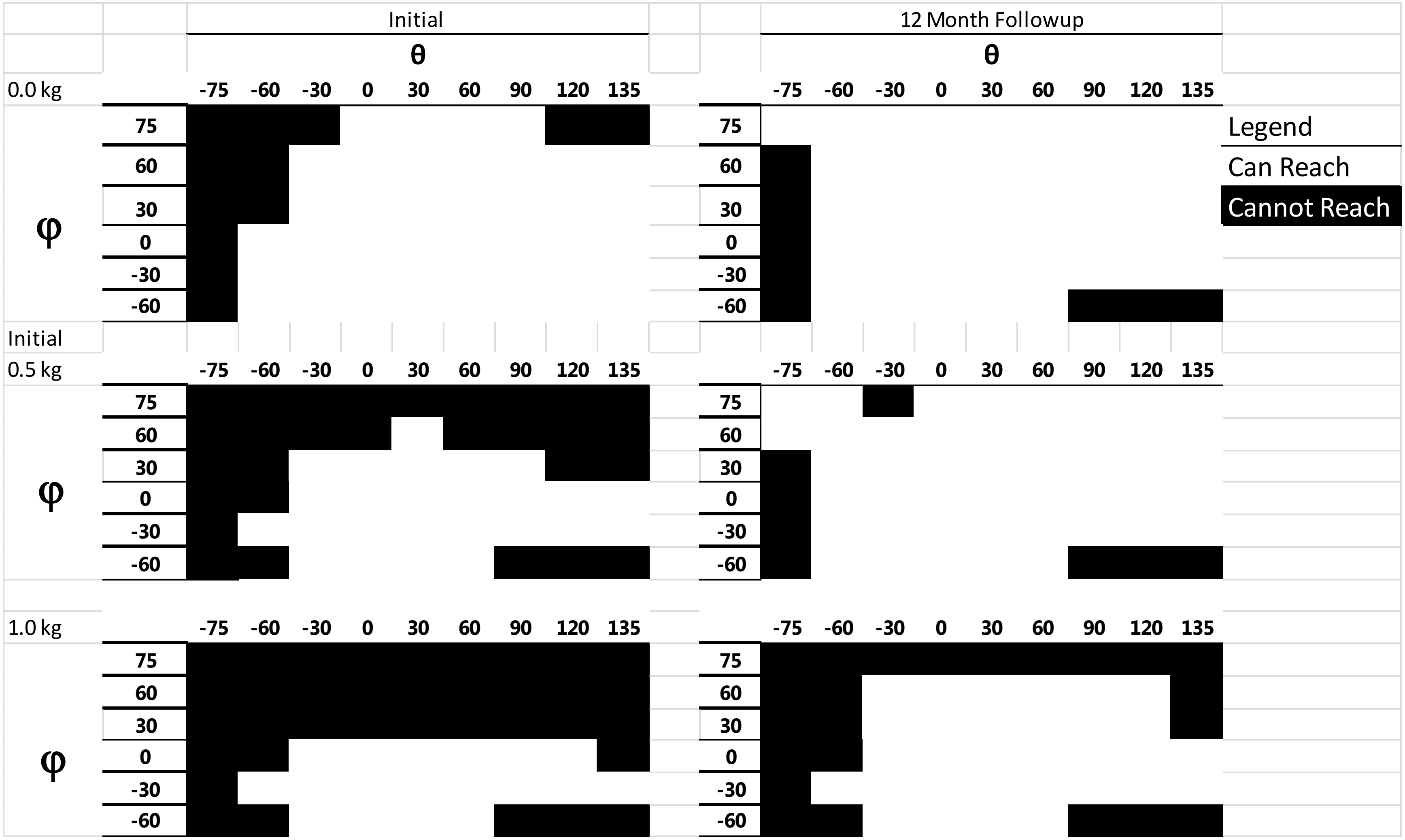


Figure 20: SYM003 MREs pre and 12 months post-surgery

This continues in the statistical results, with the largest difference being in the 1.0 load condition post-surgery (Table 24). The largest change in reach length was seen in the no load condition. There was less variability within reach lengths following surgery (Figure 21).

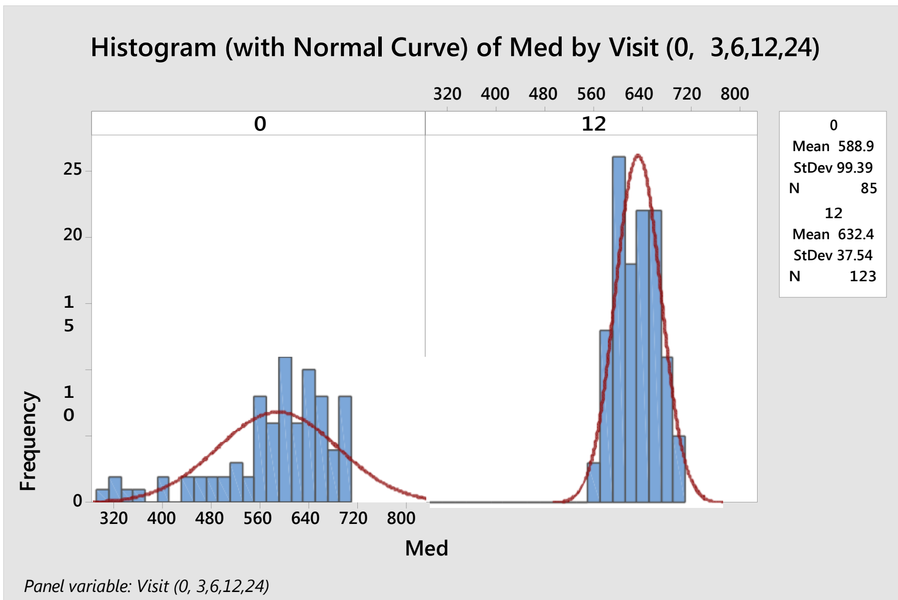


Figure 21: Histogram of median reach by visit (initial and 12 months post-surgery)

Table 24 shows the most changes in count (N) values for the 1.kg condition, but there were no changes in the overall reach length when averaged throughout the volume.

Table 24: Bin counts and overall mean reach by load condition

	Pre-Surgery			Post-Surgery			
Load (kg)	N	Nmissing	Mean (mm)	N	Nmissing	Mean (mm)	Overall Reach Difference (mm)
0.0	42	12	544	46	8	637	92
0.5	25	29	635	46	8	637	1.9
1.0	18	36	627	31	23	618	-8.9

From Tukey's pairwise comparisons (Figure 22) of the general linear model, there were differences between the no load condition and loaded conditions, but not between the 0.5 kg and 1.0 kg conditions for this participant.

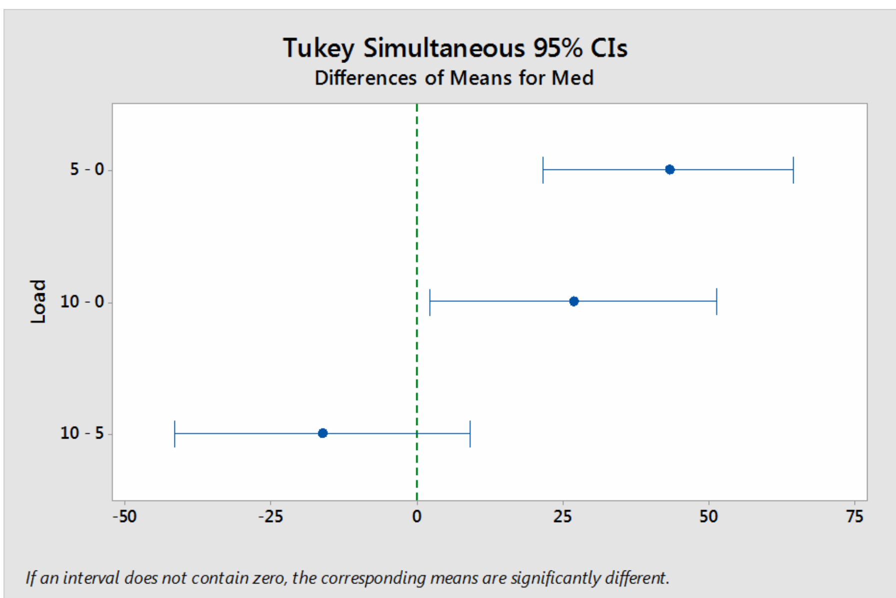


Figure 22: Tukey's post-hoc comparisons by load condition

The pairwise results for the median reach in theta (horizontal bands) show that bands 1, 8 and 9 all are similar with the largest mean length. This indicates that when reaching more than 75^{o} behind shoulder is similar to reaching more than 105^{o}

in front of the body. It was found that the theta bands adjacent to these extreme reaches (1, 2, 7, and 8) also are similar in reach lengths, with the more central bands (2, 3, 4, 5 and 6) also showing similarities, with the lowest mean reach values.

For the phi (vertical) bands, there were only 2 main group effects found. Phi bands 1-4 contained similar mean reach values which were slightly larger than the 2nd group. The 2nd group contained all phi bands other than band 2 (-45^{o} to -15^{o}), which has the overall largest mean at 653.9mm.

Range of motion values (Figure 23) show positive or no change in all values with the exceptions of active flexion, and CPSAM horizontal flexion.

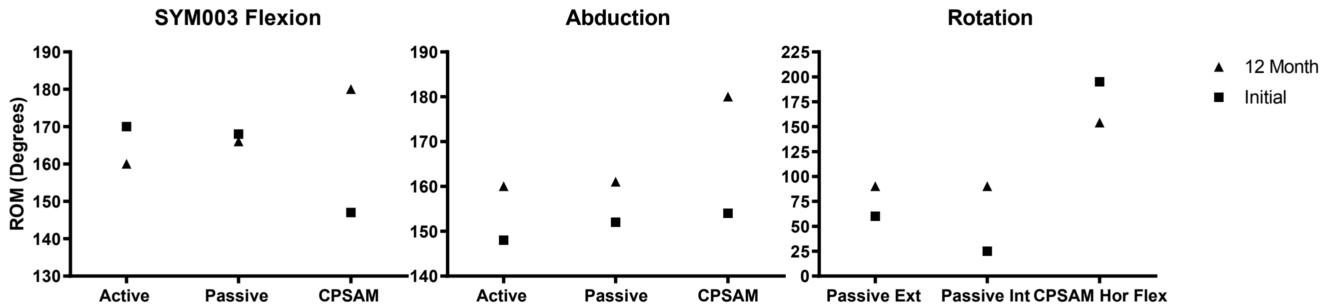


Figure 23: ROM measures for SYM003

There were large improvements in all strength measure after 12 months recovery (Figure 22).

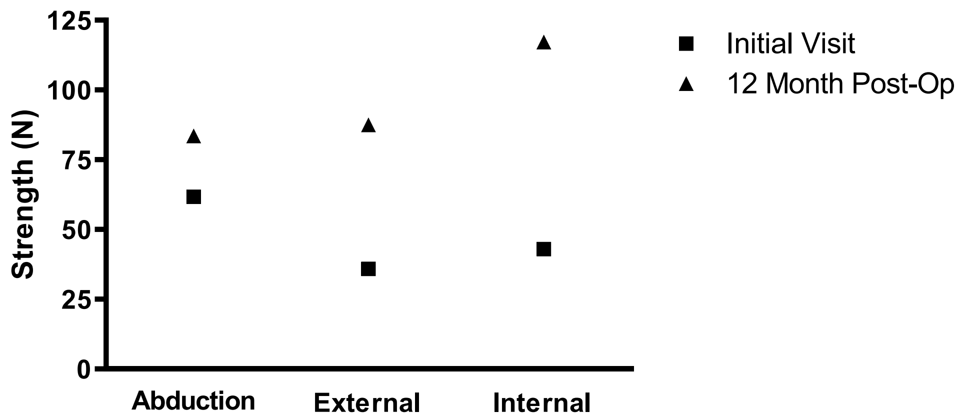


Figure 24: Strength measures for SYM003

6.4 Discussion

The goniometric ROM values vary in both participants, with positive and negative changes. For SYM003, these may indicate issues with reaching across the body, or above shoulder height, but do not seem to be reflected in the MRE. For SYM017 there were improvements on the side of the body for reach that are not reflected in the ROM measures. These may be a result of the repeatability of goniometric measures (potentially different researchers collecting) (Riddle, Rothstein, & Lamb, 1987), or differences in compensatory motions made by the participants during goniometric measures that were not possible during longer collections.

Minimal changes to strength at 3-months post-operation as opposed to larger improvements at 12 months post-surgery are logical due to the length of healing time, in addition to the strict physiotherapy requirements following repair surgery. It could be postulated that at 24months further improvements to both strength and ROM would be seen as the person fully returns to their normal activities of daily living; however the physiotherapy requirements are reduced at this time, so there may be a plateau.

The differences in reach length may be due to several factors; the participant may still be guarding their shoulder from potential pain, not extending their arm fully or avoiding areas where they previously or currently may have pain. The differences between the loaded an d no load conditions are consistent with what was seen in the pilot work (Johnston et al., 2016) for symptomatic participants, and it may be postulated that the symptomatic participants may never follow the same pattern after an injury, but more data is required at this time.

With so few follow-up visits there is not enough statistical power to comment on the functional ability of a person 3 months post operatively to return to work. With respect to the one case, only small changes occur in reach, range of motion and strength.

Functionally, the participant can be categorized as similar condition to their initial visit. At 12 months post operation, there has been an increase in reach length through the volume, particularly within the weighted testing. These improvements in functionality should translate into better ability to perform activities of daily living, including work related tasks. At present, these two examples should be used a referential case study, not as indicators of the entire symptomatic cohort.

There are many reasons for lack of participant retention; persons not living near the testing facilities, inability to establish contact in a timely manner, several re-tears, persons choosing to not have surgery, or surgeries getting postponed. Another potential reason may be that there is no longer incentive for participation in a study following the initial assessment.

Some potential sources of error in these comparisons include small differences in land marking the acromion between sessions leading to changes in the reach lengths, and therefore the ability to overlay these MRE's. A proprioceptive aid is used to minimize trunk motion during MRE collections; however there could be some minor motions in the trunk, as well as bending of the elbow during the collections. These will lead to artificially inflated/deflated values of reach, although these were monitored by researchers visually to minimize.

Chapter 7.0 Standard Clinical Measures

7.1 Introduction

In addition to the ergonomics measures of reach and anthropometry, a series of standard clinical measures were recorded on the symptomatic and age-matched asymptomatic participants. These measures included clinical measures of range of motion, strength and self-reported values related to shoulder function. Also, there was a comparison of the values extracted from the ergonomics assessments to compare with the standard clinical measures. This chapter is devoted to those measures.

7.1.1 Range of Motion and Strength Measures

To date, no study has specifically defined how a shoulder injury, such as a rotator cuff tear, or aging will impact reach measures or workstation design. Changes in clinical measures of range of motion (ROM) and strength values with injury and following repair have been reported on in orthopedic journals (Cofield et al., 2001; MacDermid, Drosdowech, & Faber, 2006; Tauro, 2006). As formally considered an important outcome measure, particularly when paired with survey results, these measures have common clinical use for example, Namdari et al reported that some loss of ROM can be well tolerated so long as there is no pain. More substantial ROM loss, specifically where there is pain can be disabling (Namdari et al, 2010). Loss of ROM is common both pre and post-surgery and tends to be related to muscle tear size, age and overall glenohumeral joint stiffness (Robinson, Lam, Walton, & Murrell, 2017b; Tauro, 2006). Reduced or compromised ROM can impact a person's ability to successfully perform occupational tasks, activities of daily living, which can impact not only physical, but mental well-being.

As humans age, changes in strength and ROM generally occur for a variety of reasons, with one being that by the age of 70, 30-40% of shoulders have some evidence of rotator cuff tears or disease (Kim et al., 2009; Roy et al., 2009; Tempelhof, Rupp, & Seil, 1999) without having pain or noticeable symptoms. These tears can impact ROM and strength, but without pain are not considered a serious concern (Robinson et al., 2017b). There is variation in the reported values of ROM and strength measures relating to the shoulder due to cohort size and recruitment capabilities. Overall it is known that men are generally stronger than women by about 60%, with strength making marked decreases after 60 years of age for men and 40 for women. ROM tends to be larger in women, but there are changes with aging in all planes of motion other than internal rotation. Reports of the impact of shoulder dominance are conflicting (Barnes, Van Steyn, & Fischer, 2001; Kim et al., 2009; Robinson et al., 2017b) with different planes showing different responses based on cohort.

Expected ROM values for persons with asymptomatic shoulders, both active and passive is shown in Figure 25 with the first cluster being forward elevation (flexion), abduction, internal rotation, external rotation, external rotation-adduction and extension (Barnes et al. 2001). These values are higher than persons with rotator cuff injuries with Robinson et al (2017b) reporting for flexion as summarized in Figure 25.

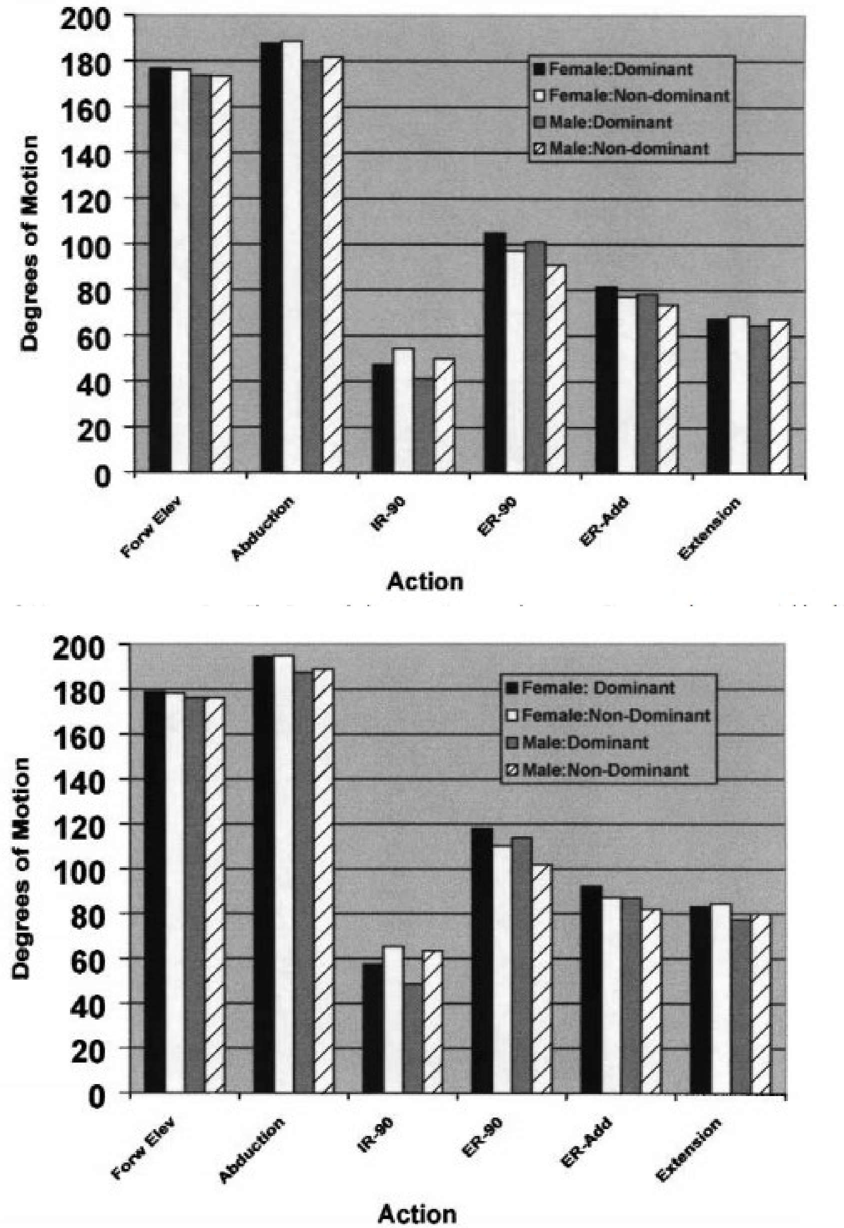


Figure 25: Active (upper) and passive (lower) ROM for asymptomatic shoulders

Table 25: Pre and post-operative ROM and strength values for shoulders

	ROM (Degrees)				Strength (N)		
Pre-op	Forward Flexion	Abduction	External Rotation	Internal Rotation	Abduction	External Rotation	Internal Rotation
	143 (3)	123 (3)	47 (2)	7.7 (0.3)	64 (3)	47 (2)	62 (3)
Post-Op	151 (3)	132 (4)	50 (2)	9.5 (3)	72 (3)	45 (2)	74 (2)

It can be challenging to compare outcomes from the current literature as each study reports ROM and strength in slightly different ways, for the same clinical measures. Roy et al have reported asymptomatic strength in Newton-metres, while the values presented in **Table 25** are in Newtons. ROM studies report results as either a comparison of differences between dominant and non-dominant sides, or as degrees of deficit. The values presented are presented as an absolute position value and are the clearest for comparison (Barnes et al., 2001; Kim et al., 2009; Robinson et al., 2017b; Roy et al., 2009).

The objectives for this section of research was compare the clinical measures of ROM, muscular strength and clinical, self-reported scores for the shoulder between the symptomatic and age matched asymptomatic groups. An additional objective was to compare the clinical ROM measures of the shoulder to functional kinematic information obtained from the MRE collections. Long term goals included the development of better methods to quantify functional measures in the RCT group.

7.1.2 DASH and WORC Survey Responses

Health related quality of life surveys give clinicians a method to assess and monitor the ability of a patient to function through their activities of daily living, as well as to lend insight into their psychological well-being (Kirkley et al., 2003). This can be particularly important when patients are off-work, or injured for extended periods of time. Shoulder injuries cannot be looked at strictly from a biological scope, as it impacts all aspects of day to day life (Hudak et al., 1996). Minimizing pain and increasing function during wait times can have dramatic impacts on all aspects of quality of life. These different functions can be difficult to measure empirically, and many scales have been developed to assist. Some are very general, looking at overall health, while others are more specific to a injured region. These self-reporting surveys are frequently used as a metric for overall improvement following a procedure (Björnsson, Norlin, Johansson, & Adolfsson, 2011; Brewer et al., 2000).

The Disabilities of the Arm, Shoulder and Hand questionnaire (DASH) was developed by 3 groups; The American Academy of Orthopedic Surgeons, the Council of Musculoskeletal Specialty Societies and The Institute for Work and Health (Toronto, Ontario). It was designed to be a measure of functional status and symptoms in an effort to quantify changes during treatment and recovery with a focus on the musculoskeletal issues in the arm, shoulder and hand (Hudak et al., 1996). The survey consists of 30 questions rated from 1 -5 by the patient, where 1 indicates no problems or disagreement with the statement and 5 is extremely or unable to do the task. Questions are divided into subsections where the wording of the 1-5 rating changes slightly. There are then two optional work and sport sections with four questions. The rating is then found by dividing the sum of scores by the number of questions answered, subtracting 1 and multiplying the result by 25. This leads to a percentage score out of 100 where higher numbers indicate a greater level of impairment. The survey has been validated by the authors and several external sources (Atroshi et al., 2000; Kirkley et al., 2003; Kitis, Celik, Aslan, & Zencir, 2009; MacDermid et al., 2006).

The Western Ontario Rotator Cuff Index (WORC) was developed by physicians and researchers (Kirkley et al., 2003)to be a disease specific quality of life measurement tool for patients with rotator cuff disease. Each question (21 total) is rated using a visual analog scale. The participant makes a mark on the scale between 1 and 100, and this is measured to get the score. The questions are separated into difference sections; physical symptoms, sports/ recreation, work, lifestyle and emotions. This is scored as a percentage in each section, as well as an overall score. A number closer to 100 indicates a participant is experiencing a lower quality of life as a direct result of the shoulder. Following repair surgery, this number should decrease. Testing of tool reliability and validity was done by the authors; who found that there were strong interclass correlation coefficients between the DASH and the American Shoulder and Elbow Surgeons Standardized Shoulder Assessment form (ASES).

The WORC and DASH have both been widely used to help clinicians quantify changes in quality of life during the recovery process, as well as the reliability and validity corroborated by outside investigators. A novel comparison approach was taken by MacDermid et al, (MacDermid et al., 2006) that tested the change in survey responses 1 week prior to surgery and 6 months post operatively. They divided the respondents into 3 groups; positive, negative and equivocal. Of the 149 participants; 86 reported improvements (positive) following surgery, with 36 having varying responses to different surveys, and 15 having negative outcomes across all surveys. This approach tackles the criticism of self-reported scales, and the challenges of validation. It was found that the DASH and WORC were quite responsive to changes in patient quality of life, with the note that negative responders appeared to really suffer mentally with the poor surgical outcomes. They were unable to choose a best survey overall, so using them in tandem is common practice.

As DASH and WORC can help quantify level of impairment when used in tandem with more empirical findings such as range of motion and strength, it is important to understand where a cohort lies on each with respect to similar studies. There are currently few published studies that compare DASH and WORC scores pre and post operatively in a longitudinal manner. Several studies indicate that, following a successful rotator cuff repair surgery the average value for the WORC has been 75. MacDermid et al. published baseline and 6 month follow-up scores; however comparing average WORC score is difficult as they summed the categories for averages so the value is no longer a percentage. Reported baseline WORC scores range from 20.1 in emotions to 39.7 in physical symptoms across the 3 groups. At 6 months follow-up the between group differences increase, with the positive responders improving to 8.4 in emotions to 17.8 in physical symptoms, with the equivocal responders ranging from 17.6 to 33.1. Of note is that the scores in the categories always increase from the lowest score in emotions, then lifestyle, work and sports/recreation having similar values, with physical symptoms having the highest score. For the DASH results, the positive responders improved from 50.6 to 26.3.

The objectives for this section are to ensure that the RCT Symptomatic group is a representative group of participants prior to surgery. Secondly the symptomatic and asymptomatic participants will be compared to further validate them as a useful tool for separating symptomatic from asymptomatic participants. Long term goals include tracking the improvement of the survey scores at follow-up appointments to compare if improvements in survey results can be traced back to improvements in ROM and strength. This cannot be done at this time as not enough follow-up data has been collected.

7.2 Methods

7.2.1 Range of Motion and Strength Measures

Reach envelope data has been collected from 22 seated, asymptomatic age matched participants and 19 participants with total RCT using the Computerised Potentiometric System for Anthropometric Measures (CPSAM) (Das et al., 1994). Each participant completed 2 side and 2 front facing trials for each of 3 handheld load conditions; no load, 0.5 kg and 1.0 kg. Trials were 45 seconds at a collection rate of 20 Hz, yielding 3800 data points following the protocol described by Johnston et al (Johnston et al., 2016). Due to the effect of the shoulder injury, in some cases the data collection methods were varied for the symptomatic participants. Typically, this was accommodated by providing more, shorter duration trials with longer rest periods between trials.

Clinical ROM values (flexion/ extension, internal/external rotation, ad/abduction) were collected using a goniometer (Lafayette Instrument Co. Model 01135), utilizing standard clinical assessment methods prior to MRE testing, described in APPENDIX C. Active ROM values for ab/adduction, flexion/ extension and horizontal flexion/ extension were calculated using the Cartesian coordinate values from the reach envelope data. These were calculated using the maximal and minimal points +100mm of either direction of the acromion in each plane, then using tangent function to find arm angles. These values were imported into Minitab for statistical comparisons including descriptive statistics and tests for normality. Most values were not normally distributed, so Mood's Median test was used for all comparisons between groups and Mann-Whitney tests were used for between measurement types (active, passive, CPSAM). In cases where there was normality, 2 sample student t-tests were used.

For passive internal and external rotations, the same testing repeated in the Orthopaedic. Each of the 5 options on these tests was given a number.

Table 26: Active external and internal rotation testing

External Rotation	Internal Rotation	Score
Hand behind Head, Elbow forward	Buttock	1
Hand behind Head, Elbow back	Lumbosacral Junction	2
Hand to top of Head, Elbow forward	Waist (L3)	3
Hand to top of Head, Elbow back	T12 Vertebra	4
Full Elevation from top of Head	Interscapular (T7)	5

Additionally, for the range of motion values pulled from the MRE data (referred to as CPSAM ROM), there was data available for 16 younger, university aged participants. These data were used for statistical comparisons between the 3 groups, using general linear models with Box-Cox transformations to correct for non-normal data.

Strength measures for subscapular, external rotation and internal rotation were taken using force transducer (Mark-10 Force Gauge Model M3-200) using standard clinical assessment measures shown in Appendix B. These tests were done following MRE testing to ensure that the symptomatic participants focused their efforts on that testing, and not potentially fatigue themselves with strength measures. Each measure was taken 3 times, with encouragement, and the results averaged.

7.2.2 Dash and WORC Surveys

All symptomatic (N=21) and aged matched (N= 23) participants tested were included for the comparison of survey values regardless of the viability of reach data. There were several participants in each group who did not complete the surveys including ASYM003, ASYM006, ASYM009, SYM006, SYM009, SYM015 and SYM020. There were issues contacting the participants by both research groups (Dr. Wong's and BENLab).

The symptomatic participants completed the surveys via ORTech through an email link sent prior to their appointment. Results were then compiled by Dr. Wong's team. Asymptomatic participants prior to ASYM012 were emailed the forms to fill out and return. ASYM013 onward completed paper copies of the form during their testing session.

All results were then compiled in Excel, and then moved into Minitab for statistical analysis including descriptive statistics and 2 sample student t-tests. It should be noted that in the DASH survey there are optional sections for work and sport, so the N missing values in these is higher where there were participants who were not active in sport or work. For the work section N_{SYM}=7 and N_{ASYM}=15. For the sport section N_{SYM}=6 and N_{ASYM}=14. Comparisons between the goniometric ROM measures were also completed using both Spearman Ro and Pearson correlations.

7.3 Results

7.3.1 Range of Motion and Strength

Testing for normality showed that only passive internal rotation and CPSAM horizontal flexion were normal, with all other measures being non-normally distributed with p-values significantly less than 0.05. All 3 strength measures were normally distributed. Table 27 shows the mean and standard deviations for the age matched and symptomatic participants. The sample size in CPSAM Abduction is one smaller as one participant was not able to reach into that plane during their MRE testing.

Mann-Whitney tests were used to compare each of the flexion medians to each other, with no differences found between the 3 methods; active, passive and CPSAM. These same tests in the abduction medians found that the CPSAM median was different from both active and passive ($p<0.005$, $p<0.01$), but there was no difference between the traditional method medians.

Comparing between the age matched and symptomatic participant groups, Mood Median testing was used for all the non-normal measures. All tests showed that there were significant differences between groups in each measure with p-values much less than 0.05 in each case. A 2-sample student t-test of CPSAM horizontal flexion showed significant differences between the 2 groups ($p<0.008$), with the age matched age asymptomatic participants having greater horizontal flexion than symptomatic participants. The t-test of internal rotation also showed significant differences with aged matched asymptomatic again having larger ROM for this plane ($p<0.02$).

Table 27: Age matched ASYM and SYM ROM

	Active Flexion (Deg)	Passive Flexion (Deg)	CPSAM Flexion (Deg)	Active Abduction (Deg)	Passive Abduction (Deg)	CPSAM Abduction (Deg)	Passive External Rotation (Deg)	Passive Internal Rotation (Deg)	CPSAM Horizontal Flexion (Deg)
ASYM n=22	168 (11)	172 (7)	173 (10)	163 (14)	163 (11)	173 (11)	84 (10)	67 (11)	149 (15)
SYM n=19**	136 (33)	150 (29)	139 (28)	109 (37)	129 (25)	141 (29)	61 (15)	55 (13)	135 (14)

** n= 18 for CPSAM Abduction

For internal rotation, the mean of the age matched participants was 4.4 with a standard deviation of 0.66 and symptomatic was 3.4 with standard deviation of 1.4. The Mood Median test showed no difference between the 2 groups. Tests for active external rotations based on the 1-5 scale were not able to be reported simply as number comparisons as many of the participants were able to complete some pieces of the 5 parts, but not all for external rotation tasks as can be seen in Figure 26.

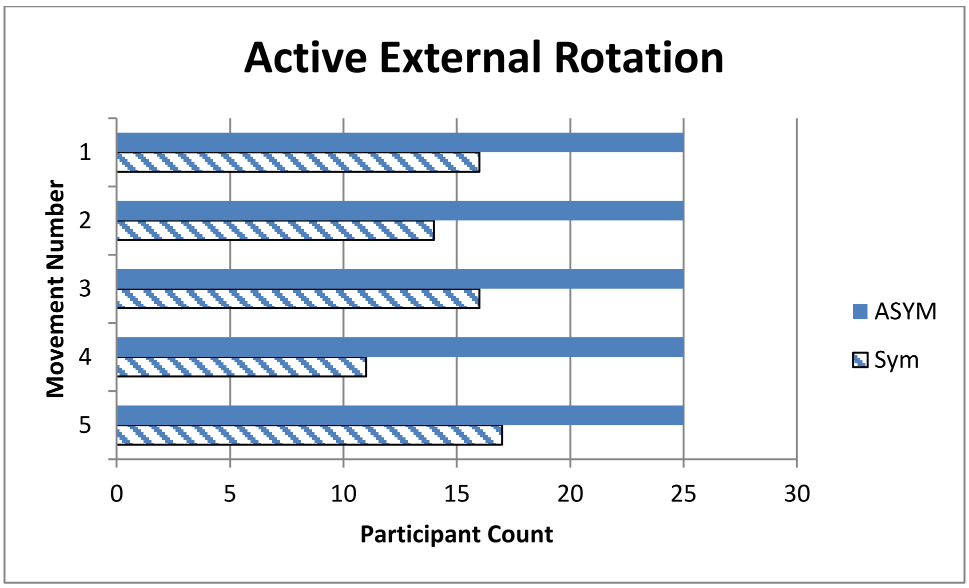


Figure 26: Active external rotation comparison

When the symptomatic ROM measures were compared to Robinson's published values using a t-test, no differences were seen in forward flexion. Abduction was the same as measured active and passive measures, but was greater than the measure from CPSAM ($p=0.016$). Both internal and external rotation were significantly different from reported values, with current measured values showing larger ROM ($p<0.001$ in both comparisons).

Mean strength measures for both groups can be seen Table 28. For each of the measures the aged matched asymptomatic values are greater than the symptomatic participants, with standard deviations being comparable. Comparisons between the 2 groups were done using 2 sample student t-tests and showed significant differences in each of the measures with the asymptomatic group being consistently higher. An interval plot of the group means with confidence intervals can be seen in Figure 27.

Table 28: Mean of strength measures

	Abduction (N)	External Rotation (N)	Internal Rotation (N)
ASYM	143 (40)	108 (35)	126 (43)
SYM	73 (42)	56 (35)	83 (46)

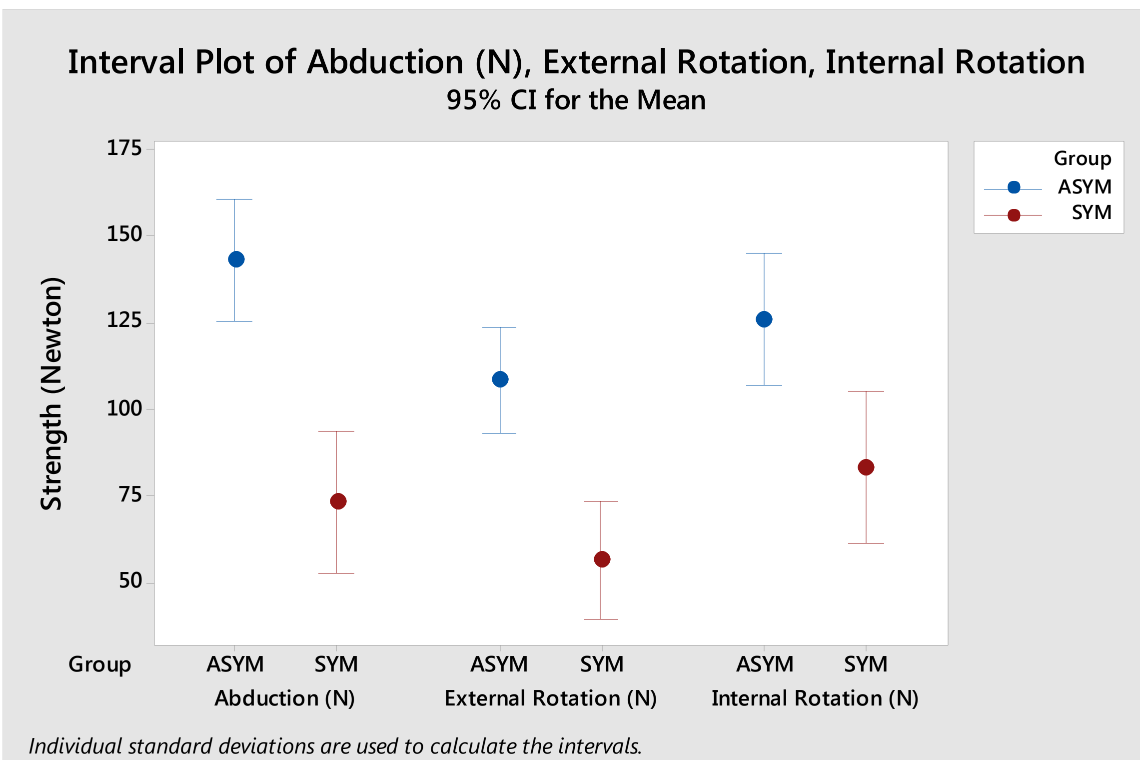


Figure 27: Comparison plot of strength measures between ASYM and SYM

When compared to published values for strength (Robinson et al., 2017b), measured values for internal rotation were found to be different ($p<0.003$) with reported values being larger. No differences were seen between reported and measured abduction and external rotation strengths.

7.3.2 DASH and WORC Surveys

The results for the WORC index are seen in Table 29 with the DASH in Table 30. The different pieces of the WORC are scored with 100 being the best score (meaning limited issues in each question) whereas the DASH is opposite with 0 meaning limited issues. It can be seen that there is a lot more variability in the symptomatic participants than the asymptomatic, in addition to the large difference in average scores.

Paired t-tests comparing the 2 groups showed significant differences between the two groups with every p- value being less than 0.002. The confidence intervals for the differences in means did vary somewhat in breadth based on the level of standard deviation in the particular section. These means and intervals (low to high value range) can be seen in Table 31. Values for DASH values were changed to positive values for easier comparisons.

Table 29: WORC overall results

	N ($N_{missing}$)	Physical	Sports/Rec	Work	Lifestyle	Emotion	Overall
ASYM	20(3)	97.7 (6.1)	97.7 (6.0)	98.3 (4.7)	99.4 (1.2)	99.6 (1.3)	98.6 (3.1)
SYM	18 (3)	53.9(21.9)	52.7 (31.9)	54.9 (25.3)	50.0 (30.8)	43.5 (22.2)	48.1 (19.8)

Table 30: DASH overall results

	N ($N_{missing}$)	Work**	Sport**	Overall
ASYM	20(3)	0.8 (3.2)	1.8 (5.2)	3.2 (7.4)
SYM	18 (4)	63.6 (30.6)	70.6 (20.7)	49.6 (20.9)

Table 31: Differences of means with 95% confidence interval

		Difference	Low Score	High Score
	Physical	43.8	32.6	55.0
WORC	Sports/Rec	45.3	29.2	61.3
	Work	43.4	30.7	56.1
	Lifestyle	42.4	30.4	54.3
	Emotion	56.1	45.1	67.2
	Overall	50.6	40.6	60.5
	Work**	62.7	34.2	91.3
DASH	Sport**	68.8	46.8	90.8
	Overall	46.4	35.6	57.3

**There is larger variation in the sport and work differences due to the reduced number of participants who completed this section.

Active ROM values (flexion/ extension, ab/adduction) were compared to the overall DASH and WORC scores first as direct comparisons using Pearson Correlation coefficients, then by rankings using Spearman Ro correlations. In both cases, there were only weak correlations with values seen in

Table 32. The exception is the ranked WORC score with the ranked angle from theta band 1 (-75:-45 degrees), however it is important to note that many of the symptomatic participants did not have scores in this band.

Table 32: Spearman Ro correlations of ROM and survey scores

	Rank Theta	Rank Flexion	Rank Abd
Rank Flexion	-0.551		
Rank Abduction	-0.563	0.758	
Rank WORC	-0.865	0.484	0.587
RANK Dash	0.473	-0.472	-0.499

Table 33: Correlations between Maximum Reach Angle in Theta and Active Flexion

	ASYM	Active Flexion	Theta Band							
			>-75	-60	30	0	30	60	90	120
Theta Band	>-75	-0.386								
	-60	-0.138	0.998							
	30	-0.03	0.961	0.744						
	0	-0.106	0.801	0.599	0.957					
	30	0.003	0.726	0.579	0.928	0.956				
	60	0.058	0.971	0.530	0.870	0.868	0.921			
	90	-0.049	0.976	0.528	0.839	0.839	0.885	0.836		
	120	-0.048	0.967	0.710	0.719	0.691	0.754	0.750	0.880	
	>135	0.132	0.993	0.811	0.541	0.447	0.513	0.491	0.514	0.750

	SYM	Active Flexion	Theta Band							
			>-75	-60	30	0	30	60	90	120
Theta Band	>-75	-0.211								
	-60	0.557	*							
	30	0.551	*	0.800						
	0	0.334	*	0.787	0.748					
	30	0.317	*	0.741	0.614	0.968				
	60	0.177	-0.881	0.616	0.500	0.918	0.974			
	90	0.189	-0.781	0.628	0.488	0.910	0.965	0.966		
	120	0.213	-0.711	0.772	0.570	0.884	0.908	0.869	0.955	
	>135	0.258	-0.461	0.880	0.455	0.663	0.735	0.385	0.598	0.771

7.4 Discussion

7.4.1 Range of Motion

As goniometric measures were not taken with the pilot young asymptomatic participants, values for only 3 of the 16 participants were available for comparison. This does not have enough statistical power to compare ROM of this group to the age matched asymptomatic and symptomatic participants, so they were not included in these results and will be filled in as future work.

All ROM measures were found to be larger in the age matched asymptomatic participants than in the symptomatic group, which is to be expected given the nature of a RCT. Namdari presents pre and post op ROM values as percentage of contralateral side which makes comparison challenging (Namdari & Green, 2010). This was not done in our study as there was evidence that a number of participants were on wait lists for contralateral injuries. Particularly in an older population, this can be a problematic comparison as there is greater probability of some type of rotator cuff disease in older persons (Kim et al., 2009; Roy et al., 2009; Tempelhof et al., 1999). When compared to Robinson's large cohort study, active and passive abduction, and all flexion measures are similar. There is a difference with the CPSAM Abduction, internal and external rotation measures.
With regards to the ROM values pulled from CPSAM data, it is of particular interest that the flexion value is comparable to traditional measures, but abduction is not (Robinson et al., 2017b; Roy et al., 2009). It was observed during MRE collection, and can be seen in the MRE section, that the regions where symptomatic participants struggled to reach were on the side of the body, and when the arm was across in front of the body. This

potentially has an impact on where a person can move their arm in space comfortably, but it appears that when asked to do this on their own time they are able to push themselves past where they think they are capable for active and passive measures of abduction. There are small differences that were not significant between the flexion measures with the CPSAM and passive measures being slightly smaller than the active. This may be the beginning of an indication that joint stiffness can change comfort levels in the frontal plane (Tauro, 2006), but a larger sample size and strength measures would be needed to confirm this.

With regards to using the ROM values from the MRE to yield a better picture of what participants are functionally capable of for design of spaces, there are still serious limitations to using just planar measures to achieve this. Neither flexion, nor abduction are able to fully capture the abilities of person, although the CPSAM horizontal flexion does give a good starting point as it can be directly related to table top work values. The one caution with this is that the axis is the acromion, and not the table or elbow, so the values are slightly above the table. That being said, work in the maximal reach envelope is not a particularly safe way to design (Das et al., 1994; Stoudt, 1973). In knowing the maximal horizontal flexion values, it can be interpolated that when the elbow is bent, this range may be slightly larger in an angular sense, but designing within these parameters will minimize potential pain.

Strength measures for all 3 planes tested, showed values for the symptomatic group were consistently lower than the age matched asymptomatic group which is as expected with a full thickness tear in one of the rotator cuff muscles, as all symptomatic participants were. The strength values for abduction and external rotation for the symptomatic group were comparable to published studies, while the internal rotation values measured were much higher. It was already known that there would be strength differences for people with RCT, from discussions with the clinicians, and within these measures themselves, specific applications to design are not there. These comparisons to published values do help boost the case that a representative sample of persons with rotator cuff tears has been studied, as currently the cohort of this work is relatively small. Future work will expand sample size, and continue to develop comparisons to help accommodate persons with RCTs match their activities of daily living to their capabilities.

7.4.2 Surveys

In comparison to other RCT studies, the WORC values for pre-surgery are slightly higher respectively than those reported by MacDermid et al. (MacDermid et al., 2006) meaning they were slightly more functional. There is no mention as to whether preoperative physiotherapy was prescribed for that cohort, as it was for the symptomatic participants. Adherence to a physiotherapy program may improve abilities to perform activities of daily living, which may be detected in the more shoulder specific WORC index. Values for DASH appear similar at about 50, which is slightly higher (again more functional) than Namdari (Namdari et al., 2010). There is no mention of the work or sport pieces of this. Asymptomatic scores were as expected in an age matched population showing no symptoms of RCT.

The reason for the large variation in the symptomatic scores can simply be attributed to having different size tears in different muscles, leading to changes in pain and function. The large differences between the means of the two groups highlights the impact of a

RCT on activities of daily living, and the ranges in the 95% confidence intervals may be a result of different tear locations and sizes. This cannot be tested without a much larger sample size, with further input on tear size and location from clinicians.

When comparing the survey results to the range of motion goniometer and CPSAM theta bands using Spearman Ro correlations, the relationships were found to be weak to moderate at best, with the exception of the maximum reach angle pulled from the CPSAM theta band one. These correlations to ROM are slightly higher than those presented by Kirkley et al. of 0.39, but are reasonably consistent considering the inclusion of asymptomatic persons in this study. The higher inverse correlation of -0.865 found with theta band 1 and the ranked WORC is probably explained by that band having only 8 participants with ROM values, as opposed to the full 40 in the remainder of the bands.

Future work will include follow-up with the DASH and WORC in the symptomatic participants, with a focus on the time post-surgery improvement plateaus and if this goes above the WORC Score of 75 currently reported in the literature (Atroshi et al., 2000; Hudak et al., 1996; Kitis et al., 2009; MacDermid et al., 2006). With respect to the ergonomic impact of these surveys, at this time the DASH and WORC are able to help assess that a participant indeed falls within the symptomatic group as opposed to the age matched asymptomatic and that some accommodations may be needed to maintain activities of daily living including work tasks.

Chapter 8.0 Conclusions and Future Considerations

The overall goal of this research was to test and compare the maximum reach envelope and the impact of small handheld loads on the MRE for aged matched adults with no history of shoulder injury (asymptomatic participants) and participants with total rotator cuff tears prior to and at selected intervals following repair surgery. Due to time constraints and participant retention, the focus was shifted to pre-surgery visits, with case studies of those who had post repair visits. The project was developed using the WHO ICF Framework for Activities of daily living in combination with general principles from ergonomics and Industrial Engineering. The objective was to blend these research areas which included the measurement of the maximum reach envelope in combination with other physical and clinical measures of the human such as arm length, ROM, strength, posture and load. Specifically, this research addressed the following objectives:

1. Compare the effect of handheld loads on the maximum reach envelope of 3 participant groups; young asymptomatic, age matched asymptomatic and symptomatic (rotator cuff tears).

2. Compare current clinical measures related to the shoulder impairment group of static range of motion measures to measures extracted from the maximum reach measures.

3. Create knowledge translation tools to aid clinicians and participants in understanding shoulder function in relation to injury status.

8.1 Conclusions

From the results of this research the following conclusions can be made:

1. The addition of small, hand-held loads significantly decreases the reach length of MRE of the groups. This effect is most prominent in the outer reach regions of the symptomatic group, but is present in both the young and age matched symptomatic groups, especially when loads are altered.

2. Normalization of the reach lengths within the MRE to arm length allows for the creation of reach curves that can be used for design. These values are also useful for comparisons between groups as they decrease variability between participants.

3. Dynamic testing for range of motion gives a more realistic description of function during activities of daily living than static (goniometric) measures.

4. Clinically measured range of motion was found to be significantly different between the age-matched asymptomatic and symptomatic groups, and was consistent with previously reported values.

5. Strength in the symptomatic group was significantly less than that of their age matched counterparts, but there are large variations within these measures within the RCT group.

6. No correlations were found between the DASH and WORC surveys and either the clinically measured ROM or the ROM measures

extracted from the MRE.

7. Reach maps, based on the spherical coordinates are a knowledge translation tool that allows for comparison of a particular symptomatic participant's reach to their symptomatic cohorts and to see how they compare to asymptomatic participants. The reach maps show that reaching above 75^{o}, and in particular to the maximal regions of the horizontal reach areas are regions all persons struggle with, regardless of group. The presence of small handheld weight further reduces the reach in these areas.

8. PCA can be a useful tool for testing differences between groups, however interactions in models with multiple variables can become complex.

8.2 Future Considerations

There are broad applications for this research in ergonomics and health research which touch on both applied and theoretical issues in research.

1. Future investigation is needed to explain the cause of the reduction in reach length observed in the young asymptomatic group with the addition of hand-held loads, and why the effect was less in the older age-matched adults.

2. Future investigation of changes in DASH and WORC survey results as participants rehabilitate should be continued to test if there is a

correlation between improvement in perceived function to recovery of ROM, MRE and strength at follow-up testing.

3. Future work should include continual effects to compare the maximum reach waveform using PCA with respect to other variables collected such as the survey results to see if they can be added in and are of value.

This project has established a foundation for the comparison of reach among different groups. Future work which follows symptomatic participants through their recovery process to capture improvements in reach, ROM and strength may allow for the creation of a robust method to access efficacy of different surgical and non-surgical interventions

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Appendix A List of Abbreviations Used

ADL- Activities of daily living

CPSAM- Computerized Potentiometric System for Anthropometric Measure created by Kozey and Das (1994). The system uses the linear measurement of 4 recording devices to predict the position of a single point in a 3-D volume.

CSV- Comma Separated variable file, a type of output that can be read easily by Microsoft Excel and Matlab.

DASH- Disabilities of the Shoulder and Hand Survey

GCS- Global Coordinate System

ICF- International Classification of Function

MRE- Maximum Reach Envelope is the region where a person can reach with their arm while keeping their trunk still

PCA- PCA. A statistical method of pattern recognition in large data sets.

PC- Principal Component

PRU- Potentiometric Recording Unit found on CPSAM that consists of a potentiometer attached to a custom created pulley. As the string around the pulley is pulled or released, the potentiometer turns to return different voltage recordings.

RCT- Rotator Cuff Tear

ROM- Range of motion

WORC- Western Ontario Rotator Cuff Index Survey

Appendix B CPSAM Reach Study Clinical Measures

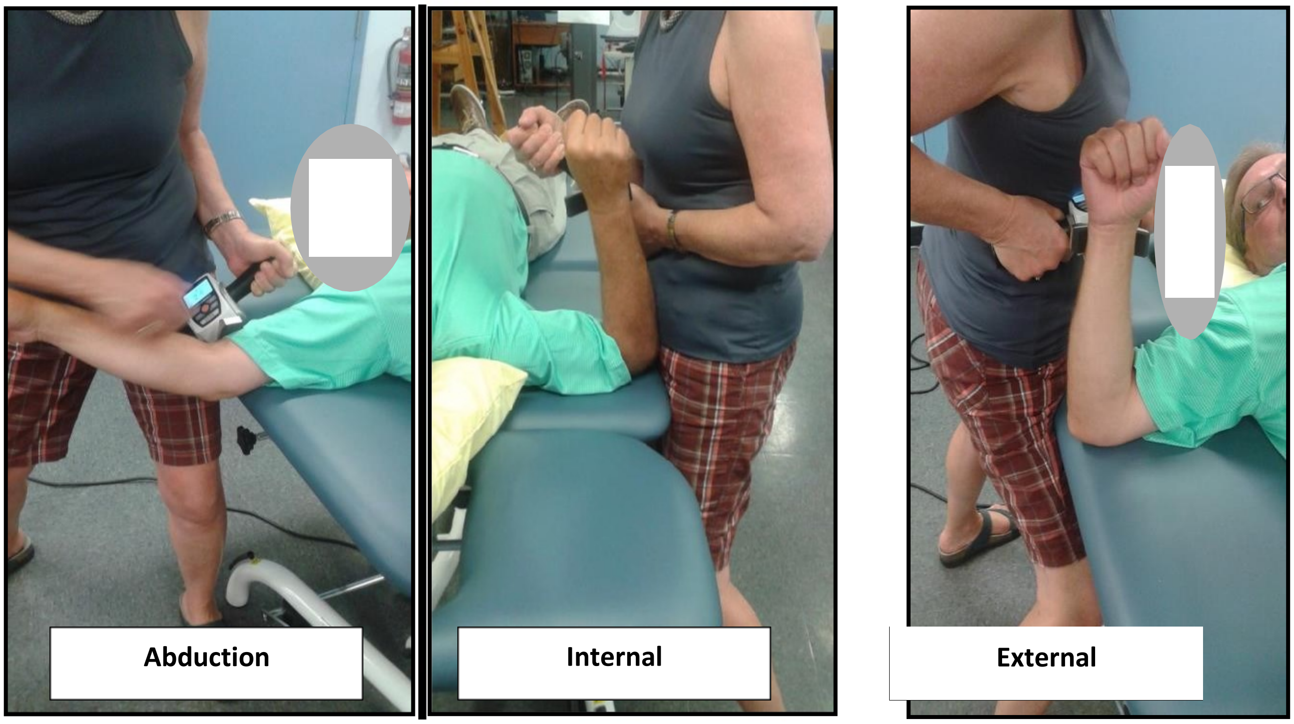
July 2016

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:
  - o Acromion
  - o Lateral epicondyle
- □ Locate point of application (superior to elbow); mark
- □ Locate point of application anterior and posterior (wrist); mark
- □ Measure in mm
  - o Distance from acromion > point of appl. Near elbow
  - o Distance from point of application on wrist > lateral epicondyle



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 2^{nd} 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 C Data Collection Sheets

CPSAM Data Collection Checklist

	Subject No.		File #	Comments
Front	T001	Bias PRU1		
	T002	Bias PRU2		
	T003	Bias PRU3		
	T004	Bias PRU4		
	T005	Chair 1		
	T006	Chair 2		
	T007	Chair 3		
	T008	Acromion		
	T009	Elbow		
	T010	Sternum Inferior		
	T011	Sternum Superior		
	T012	0.0 kg		
	T013	1.0 kg		
	T014	0.5 kg		
	T015	0.5 kg		
	T016	1.0 kg		
	T017	0.0 kg		
Side	T018	Side Chair 1		
	T019	Side Chair 2		
	T020	Side Chair 3		
	T021	Acromion		
	T022	Elbow		
	T023	Sternum Inferior		
	T024	Sternum Superior		
	T025	Side 0.0 kg		
	T026	Side 0.5 kg		
	T027	Side 1.0 kg		
	T028	Side 0.0 kg		
	T029	Side 1.0 kg		
	T030	Side 0.5 kg		

- ☐ Consent Form (Give a copy)
- ☐ ORTech Surveys (DASH, WORC)
- ☐ Clinical Measures (Record on Follow-Up Clinical Exam Sheet)
- ☐ CPSAM Trials

☐ Using Stadiometer/ Scale

Seated Head Height (mm)	
Seated Shoulder Height (mm)	
Seated Elbow Height (mm)	
Arm Length (mm)	
Standing Height (mm) w shoe	
Mass (Kg)	
Age:	
Spinal Curve:	

Appendix D: Normalization of Reach Lengths

The main analysis of the reach lengths and their interactions with load and position in space were described in the main body of the dissertation (**Chapter 3).** That analysis examined the effects of load and position on the mean values across the groups and the factors of load and position. As a supplement to that analysis the following Tables (28 to 33) are provided. These values are the mean reach values in each panel, for each of the groups. These tables are useful to examine the pattern of changes of the reach distances across the panels. For each load condition, 2 sets of 4 graphs are provided. The first set present the absolute lengths (mm) for each of the groups.

Since reach lengths are related to the arm length a second series of tables were prepared in which the absolute values are normalized to the participants arm length. The normalized values make it easier to visualize the changes in the θ-φ combination as well as seeing the changes in lengths within the tables. The normalized values can be greater than 100%, of the arm since this methodology allows for the glenohumeral and scapular motion take place throughout the MRE motion.

	θ								
YASYM	**-75**	**-60**	**-30**	**0**	**30**	**60**	**90**	**120**	**135**
75	701.0	695.8	670.4	645.9	639.4	633.2	663.4	688.1	692.9
60	724.3	691.4	658.7	635.7	633.7	654.7	686.9	713.8	727.4
30		700.7	664.9	631.3	631.7	660.9	684.3	726.3	746.1
0	742.6	718.0	679.2	652.8	631.2	663.2	688.3	737.8	761.7
-30	754.5	725.1	703.9	682.7	680.9	688.2	711.8	747.1	755.5
-60	742.5	699.6	710.4	730.3	723.3	713.1	704.4	747.2	

φ

ASYM	**-75**	**-60**	**-30**	**0**	**30**	**60**	**90**	**120**	**135**
75	662.5	683.7	651.9	655.0	655.5	662.2	659.1	685.4	677.1
60	705.8	669.1	652.7	641.7	642.1	650.9	680.6	709.5	732.3
30		695.3	655.4	639.6	635.3	651.6	681.5	730.4	751.5
0		717.8	676.7	655.9	645.5	671.9	693.8	745.4	760.0
-30	604.5	725.3	704.4	688.5	685.3	694.8	715.0	744.8	750.1
-60	604.8	716.5	720.5	711.7	704.7	703.4	713.7	749.2	

φ

SYM	**-75**	**-60**	**-30**	**0**	**30**	**60**	**90**	**120**	**135**
75	592.3	595.1	640.2	676.6	699.6	688.4	681.0	718.8	723.4
60		620.5	611.5	622.1	623.5	617.5	650.3	684.2	719.2
30		674.2	624.2	586.8	606.5	624.0	639.3	682.9	744.5
0		640.5	650.7	620.4	614.6	636.6	647.1	678.5	744.4
-30		632.5	671.9	651.6	650.1	662.2	680.9	703.0	718.9
-60		697.2	678.9	668.2	658.2	654.7	658.0	666.2	675.0

φ

Figure 28: Mean reach across MRE (0.0 kg, in mm)

θ

	YASYM	-75	-60	-30	0	30	60	90	120	135
φ	75	0.935	0.938	0.909	0.886	0.877	0.869	0.910	0.943	0.925
	60	0.997	0.964	0.905	0.873	0.870	0.898	0.943	0.974	0.985
	30		0.976	0.913	0.866	0.867	0.907	0.939	0.997	1.025
	0	1.053	0.991	0.932	0.895	0.865	0.911	0.945	1.013	1.046
	-30	1.083	0.998	0.966	0.938	0.933	0.945	0.977	1.025	1.048
	-60	1.062	0.986	0.979	1.005	0.996	0.982	0.985	1.049	

	ASYM	-75	-60	-30	0	30	60	90	120	135
φ	75	0.905	0.911	0.873	0.872	0.873	0.882	0.884	0.911	0.908
	60	0.929	0.892	0.872	0.854	0.855	0.867	0.907	0.945	0.967
	30		0.928	0.874	0.853	0.846	0.865	0.908	0.973	0.997
	0		0.966	0.902	0.875	0.859	0.894	0.924	0.989	1.004
	-30	0.828	0.979	0.940	0.919	0.913	0.926	0.953	0.993	0.977
	-60	0.829	0.959	0.958	0.946	0.936	0.934	0.955	1.002	

	SYM	-75	-60	-30	0	30	60	90	120	135
φ	75			0.848	0.893	0.921	0.909	0.899	0.898	0.929
	60		0.776	0.860	0.847	0.848	0.847	0.888	0.919	0.958
	30		0.887	0.857	0.813	0.843	0.862	0.883	0.943	1.009
	0		0.952	0.894	0.856	0.851	0.879	0.893	0.939	1.012
	-30		0.932	0.935	0.898	0.899	0.913	0.940	0.969	0.987
	-60		0.978	0.937	0.925	0.912	0.907	0.899	0.890	0.893

Figure 29: Normalized reach across MRE (0.0 kg)

φ \ θ	-75	-60	-30	0	30	60	90	120	135
YASYM									
75	596.4	656.1	626.2	620.1	649.4	610.7	643.4	643.1	683.0
60		670.2	636.7	614.5	617.9	638.2	667.2	690.8	715.3
30		685.1	648.6	607.3	608.9	625.2	659.3	709.5	721.7
0		709.2	662.5	629.8	609.3	634.8	663.4	716.9	740.0
-30	749.9	720.0	693.7	677.4	664.2	665.7	681.9	724.9	740.9
-60	692.7	679.0	687.0	713.7	702.2	693.0	648.3	665.4	

φ	-75	-60	-30	0	30	60	90	120	135
ASYM									
75	679.6	723.6	687.1	671.2	669.9	674.9	686.7	699.8	697.8
60	718.2	673.1	664.8	652.2	650.8	670.2	685.5	723.7	741.2
30		685.7	667.9	647.4	644.0	662.8	695.0	745.5	769.7
0		725.7	688.6	666.1	656.7	673.0	709.7	756.0	773.7
-30	888.9	727.3	703.0	692.8	689.7	697.9	727.5	761.8	769.1
-60	864.4	749.1	714.4	712.4	711.9	716.2	735.7	802.4	

φ	-75	-60	-30	0	30	60	90	120	135
SYM									
75	607.8	654.7	667.0	680.7	662.7	685.5	714.4	596.7	652.0
60		664.1	674.0	625.6	605.2	612.2	665.6	697.8	722.7
30		745.0	639.3	614.0	598.6	616.8	652.9	698.8	765.0
0		770.6	653.7	621.6	609.2	635.7	673.0	713.0	761.7
-30		671.8	662.5	647.1	655.7	651.7	691.5	720.1	713.8
-60		683.5	667.6	670.7	668.0	661.1	660.2	686.5	666.0

Figure 30: Mean reach across MRE (0.5 kg, in mm)

		θ								
	YASYM	**-75**	**-60**	**-30**	**0**	**30**	**60**	**90**	**120**	**135**
Φ	**75**	0.855	0.901	0.857	0.848	0.887	0.841	0.884	0.883	0.968
	60		0.926	0.876	0.845	0.850	0.871	0.917	0.949	0.978
	30		0.953	0.891	0.834	0.837	0.859	0.905	0.974	1.003
	0		0.993	0.910	0.865	0.837	0.872	0.911	0.984	1.017
	-30	1.016	0.990	0.953	0.930	0.911	0.915	0.937	0.996	1.030
	-60	0.995	0.955	0.947	0.980	0.964	0.953	0.904	0.954	

	ASYM	**-75**	**-60**	**-30**	**0**	**30**	**60**	**90**	**120**	**135**
Φ	**75**	0.882	0.931	0.897	0.888	0.890	0.890	0.901	0.916	0.905
	60	0.945	0.909	0.888	0.868	0.866	0.893	0.913	0.965	0.971
	30		0.933	0.893	0.863	0.858	0.883	0.926	0.994	1.017
	0		0.995	0.919	0.888	0.874	0.896	0.946	1.003	1.023
	-30	1.170	0.992	0.939	0.925	0.919	0.931	0.970	1.011	1.016
	-60	1.081	0.986	0.951	0.946	0.946	0.952	0.988	0.991	

	SYM	**-75**	**-60**	**-30**	**0**	**30**	**60**	**90**	**120**	**135**
Φ	**75**	0.760	0.818	0.882	0.899	0.876	0.903	0.941	0.746	0.838
	60		0.877	0.889	0.836	0.832	0.825	0.905	0.955	0.926
	30		0.979	0.883	0.842	0.824	0.857	0.905	0.953	1.014
	0		1.011	0.903	0.858	0.843	0.881	0.931	0.985	1.039
	-30		0.959	0.922	0.893	0.906	0.899	0.954	0.993	0.985
	-60		0.938	0.931	0.929	0.926	0.916	0.913	0.889	0.881

Figure 31: Normalized reach across MRE (0.5 kg)

	θ								
YASYM	**-75**	**-60**	**-30**	**0**	**30**	**60**	**90**	**120**	**135**
Φ 75	664.4	669.3	670.4	661.3	672.1	681.4	676.7	713.4	[redacted]
60	[redacted]	678.1	640.7	612.0	630.2	663.7	684.3	719.0	738.7
30	[redacted]	668.9	624.2	604.1	600.0	636.1	660.1	713.6	741.5
0	741.8	680.2	638.9	617.7	614.8	626.3	662.9	709.0	741.6
-30	[redacted]	693.4	665.3	646.5	650.5	640.0	668.8	692.9	733.9
-60	705.5	705.3	684.6	675.4	656.4	664.5	685.5	693.2	705.9

ASYM	**-75**	**-60**	**-30**	**0**	**30**	**60**	**90**	**120**	**135**
Φ 75	696.7	704.4	672.9	666.7	660.3	665.0	672.6	708.1	706.9
60	726.9	661.2	662.0	641.5	641.5	663.5	686.7	722.3	748.2
30	[redacted]	685.3	666.2	645.5	638.2	659.6	691.6	738.3	779.4
0	[redacted]	711.2	687.3	670.9	655.9	671.2	705.6	752.1	774.5
-30	[redacted]	722.1	711.0	697.3	692.3	699.5	725.0	759.5	770.8
-60	852.7	759.7	717.8	709.6	708.6	717.4	727.2	704.9	[redacted]

SYM	**-75**	**-60**	**-30**	**0**	**30**	**60**	**90**	**120**	**135**
Φ 75	[redacted]	632.5	660.4	640.5	686.1	669.6	676.2	703.9	704.1
60	[redacted]	634.8	657.7	657.0	600.7	636.1	669.5	731.8	685.2
30	721.7	701.5	697.7	613.4	582.4	593.3	636.9	695.4	730.0
0	755.3	666.8	617.3	623.3	607.1	618.3	654.4	701.3	724.6
-30	834.6	644.4	656.2	654.1	639.9	653.9	692.0	722.6	739.9
-60	[redacted]	673.9	656.9	646.3	655.9	639.0	657.3	696.1	689.0

Figure 32: Mean reach across MRE (1.0 kg, in mm)

θ

	YASYM	-75	-60	-30	0	30	60	90	120	135
Φ	75	0.956	0.943	0.917	0.904	0.919	0.933	0.912	1.005	
	60		0.929	0.876	0.839	0.861	0.907	0.935	0.982	1.027
	30		0.917	0.853	0.825	0.820	0.869	0.902	0.974	1.012
	0	1.045	0.949	0.874	0.844	0.840	0.855	0.905	0.968	1.012
	-30		0.958	0.912	0.886	0.890	0.874	0.914	0.946	0.985
	-60	0.918	0.918	0.889	0.894	0.888	0.899	0.920	0.903	0.963

	ASYM	-75	-60	-30	0	30	60	90	120	135
Φ	75	0.880	0.916	0.888	0.878	0.878	0.880	0.894	0.924	0.892
	60	0.938	0.891	0.881	0.857	0.854	0.884	0.914	0.963	0.973
	30		0.919	0.888	0.861	0.850	0.879	0.921	0.984	1.040
	0		0.970	0.917	0.894	0.874	0.894	0.941	1.000	1.021
	-30		0.977	0.949	0.930	0.922	0.933	0.966	1.012	1.005
	-60	1.066	0.991	0.954	0.941	0.945	0.952	0.974	0.963	

	SYM	-75	-60	-30	0	30	60	90	120	135
Φ	75		0.791	0.848	0.823	0.879	0.858	0.866	0.880	0.880
	60		0.793	0.868	0.857	0.791	0.842	0.886	0.976	0.874
	30	0.950	0.923	0.916	0.827	0.792	0.806	0.872	0.946	0.958
	0	0.994	0.926	0.850	0.860	0.840	0.857	0.904	0.967	0.979
	-30	1.098	0.951	0.914	0.902	0.885	0.903	0.955	0.997	1.017
	-60		0.921	0.922	0.898	0.905	0.891	0.912	0.929	0.911

Figure 33: Normalized reach across MRE (1.0 kg)

From these figures, it can be seen that in the central MRE, the values range between 85 and 90%, but there is a small downward trend with the addition of handheld weights. When reaching into regions below shoulder height, reach is longest behind the shoulder ($\theta < -60^o$), and when reaching across the body ($\theta > 120^o$). These are also known to be regions where varying amounts of participants were able to reach, which does add to the complexity of this problem.