Personalized Exercise Therapy Program for the Treatment of Individuals with Symptomatic Rotator Cuff Tears

by

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University of Pittsburgh, 2023

Rotator cuff tears continue to present an important clinical problem due to the lack of evidence supporting an optimal initial treatment method. Approximately 30% of the general population develops a rotator cuff tear and the incidence increases with age. Pain and limited capability to perform activities of daily living due to the tear emphasize the importance of determining an optimal initial treatment method. Generally, exercise therapy is prescribed as initial treatment, but some clinicians believe exercise will lead to tear propagation. However, others believe that exercise therapy restores proper function of the surrounding healthy musculature reducing the forces on the tear, thus preventing tear propagation.

Developing a better understanding of changes in function, pain and tear size following exercise therapy may improve treatment modalities and long-term outcomes. The objective of this dissertation was to determine changes in joint function, patient reported outcomes and tear size following a 12-week individualized exercise therapy program for treatment of individuals with symptomatic isolated supraspinatus tears and compare individuals successfully and unsuccessfully treated with exercise therapy. Clinicians can utilize this information to make informed initial treatment decisions, understand the risks of tear propagation and changes in joint function that occur following exercise therapy.

Individuals with isolated supraspinatus tears had minor limitations in shoulder motion and muscle strength that were not associated with altered glenohumeral kinematics or patient reported outcomes prior to exercise therapy. Individuals experienced improvements in joint function, patient reported outcomes, range of motion and strength without increases in tear size following exercise therapy. Changes in glenohumeral kinematics were associated with patient reported outcomes during a novel reaching behind the back movement resulting in new targetable factors during treatment. Validated subject specific computational models were developed that were capable of distinguishing differences in joint stability between individuals who were successfully and unsuccessfully treated with exercise therapy. The models may be used in the future as a clinical tool to direct treatment and reduce healthcare costs. Future work will investigate the maintenance of the exercise therapy program at 5-year follow-up and determine if modifications to exercise therapy protocols improve outcomes.

Table of Contents

List of Tables

List of Figures

Preface

Five years goes by in the blink of an eye. I remember visiting the Orthopaedic Robotics Laboratory for the first time. Like anyone else I was a little nervous, but fortunately Dr. Debski's first question was whether or not I enjoyed sports. Phew I can handle that I thought. Over my 5 years in the laboratory, I was able to meet and converse with undoubtedly the smartest individuals I have ever met. I now have colleagues and friends from all over the world including Japan, Germany and Italy who educated me on orthopaedic surgery and biomechanics. Above all, I attribute all my work and knowledge to Dr. Debski to whom I am extremely grateful for his mentorship and support. Dr. Debski I sincerely thank you for your guidance and effort in helping me complete my PhD. Additionally, I would like to thank the Debski family, including Mandy and Riley for your hospitality and support throughout my time here at PITT.

I would also like to thank my committee members for their efforts and support in completing my degree including Dr. Irrgang, Dr. Musahl, Dr. Anderst and Dr. Mahboobin. Dr. Irrgang, thank you for all your mentorship in the realms of research and physical therapy. Perhaps in another life I would have become a physical therapist. Dr. Musahl thank you for all of your clinical insights in orthopaedics and biomechanics. Dr. Anderst, thank you for your mentorship in biomechanics, specifically the collection and analyzation of in-vivo kinematics. Last but not least, I would like to give my utmost thanks to Dr. Mahboobin for his mentorship in computational modeling and good taste in chocolate covered almonds, espresso and affogato.

To my extended families in the Orthopaedic Robotics Laboratory and Biodynamics Laboratory past or present, I would like to thank everyone for all of their help, support and laughs throughout the years. Specifically, I would like to thank Gerald Ferrer, Sene Polamalu, Calvin

Chan, Satoshi Yamakawa, Satoshi Takeuchi, Keishi Takaba, Kengo Shimozaki, and Jumpei Inoue. I also thank all of the Orthopaedic Residents for educating me on orthopaedic surgery including Rob Tisherman, Chris Gibbs, Ehab Nazzal, and Zach Herman. My utmost thanks to members of the Biodynamics Laboratory including Camille Johnson, Tom Gale, Clarissa LeVasseur, and Alex Maxim. To my hometown, undergrad and Pittsburgh friends for there is too many to name, thank you for all the laughs and support throughout the years. Thank you for giving me a place to relax and escape the everyday stressors of the world.

I wouldn't be standing where I am today without my family. Mom and Dad thank you for encouraging my intellectual curiosity and showing me firsthand what hard work looks like. Mom, thank you for all of the physical therapy and anatomy lessons while giving me treatments after baseball games and tournaments. Your passion for treating and taking care of others inspired me to pursue what I have throughout my life, and I am forever grateful. Dad, thank you for all your hard work to enable me to be in the position I am in today. Thank you for being my rock whenever I needed help in school whether it be math, science or statistics. Furthermore, thank you for showing me what patience, hard work and a good mentality gets you whether it be on the baseball field or in life. Danny, Johnny and Kim, thank you for all the laughs and supporting me all throughout life. Danny and Johnny, thank you for playing over the top in the basement, playing catch with a baseball or playing GameCube with me. I couldn't have asked for better big brothers that didn't mind their annoying little brother tagging along.

Last but most certainly not least, my deepest gratitude and thanks to Monica, my beautiful wife. I will make sure to collect your Honorary PhD Certificate from PITT for your efforts and support. I couldn't imagine completing my PhD without you. Throughout my PhD, we made so many memories together, went on adventures, got married and bought a house. Thank you for the endless encouragement and loving shoulder to lean on. Thank you for being my forever date and love and cannot wait to see what the future has in store for us. I could not be more grateful to have you by my side and thank you again for always being there for me. Love Luke….Dr. Luke.

1.0 Introduction and Background

The glenohumeral joint is comprised of the articulation between the humeral head and the glenoid fossa of the scapula (Figure 1.1)(1). Of all the diarthrodial joints in the body, the glenohumeral joint demonstrates the largest range of motion, but is inherently less stable due to the shallow glenoid which provides less bony stability (1, 2). Although soft tissue structures such as the glenohumeral capsule and labrum provide static stability, the glenohumeral joint relies on the active function of the rotator cuff muscles to pull the humeral head into the glenoid fossa (3). The rotator cuff muscles consist of the supraspinatus, subscapularis, infraspinatus and teres minor which all originate on the scapula, cross the glenohumeral joint and insert onto the humerus.

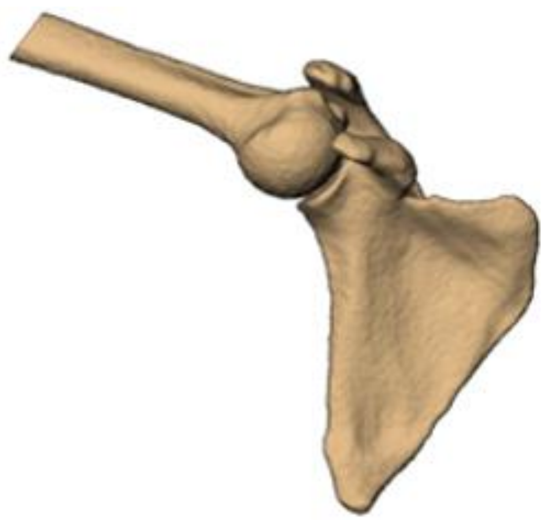

Figure 1.1: Articulation of the humeral head on the glenoid during scapular plane abduction.

1.1 Glenohumeral Joint Anatomy

The two bones that comprise the glenohumeral joint are the humerus and scapula, where the humeral head is much larger than the shallow glenoid fossa. The humeral head articulates on the glenoid and is able to translate and rotate on the articular surface. Other than the bony geometries, the major soft tissue structures of the glenohumeral joint can be separated into two groups: 1) static stabilizers and 2) dynamic stabilizers.

The two primary static structures include the glenohumeral capsule (comprised of the glenohumeral ligaments) and labrum. The glenohumeral capsule is a thin fibrous sheet of tissue that inserts on the humerus and scapula and encompasses the glenohumeral joint. Thickenings of the capsule can be visualized, and are named the superior, middle and inferior glenohumeral ligaments. Although they are labeled as ligaments, they do not act in the same manner as a typical ligament where a purely tensile force is carried along the length of the tissue (4, 5). Instead, the glenohumeral ligaments become taught at varying joint positions including abduction, internal-external rotation and flexion-extension and combinations of each. The labrum is a fibrous ring overlying the perimeter of the glenoid rim and acts to deepen the glenoid by approximately 50.0% enhancing concavity compression. The two main functions of the labrum are to act as attachment sites for the glenohumeral ligaments and to prevent glenohumeral joint subluxation (6).

The main dynamic stabilizers of the glenohumeral joint include the rotator cuff and deltoid muscles. The rotator cuff is comprised of four individual muscles including the supraspinatus, infraspinatus, teres minor and subscapularis. The supraspinatus originates from the supraspinous fossa and inserts on the superior facet of the greater tuberosity on the humerus. The infraspinatus originates from the infraspinous fossa which resides on the posterior surface of the scapula and inserts on the middle facet of the greater tuberosity of the humerus adjacent to the supraspinatus tendon. The teres minor originates on the lateral border of the scapula adjacent to the posterior surface and inserts on the inferior facet of the greater tuberosity of the humerus. The subscapularis originates on the anterior surface of the scapula and inserts on the lesser tuberosity of the humerus. Lastly, the deltoid is generally described as having three compartments, the anterior, middle and posterior deltoid. The compartments of the deltoid have varying functions depending on the joint position and movement. Generally, the deltoid is responsible for abducting the humerus and medial compression at higher levels of abduction (7).

1.1.1 Glenohumeral Joint Function

Due to the glenohumeral joint’s large range of motion and minimal stability provided by the static and bony structures, the glenohumeral joint heavily relies on the dynamic stabilizers. On an individual basis, the supraspinatus also initiates abduction, the infraspinatus and teres minor externally rotate the humerus and the subscapularis internally rotates the humerus with respect to the glenoid (6). Overall, the rotator cuff muscles act to pull the humeral head into the glenoid creating concavity compression (8). However, stabilizing the glenohumeral joint requires an intricate balance between the rotator cuff and deltoid muscles.

Two force couples are mainly responsible for the delicate balance of forces crossing the glenohumeral joint and were coined the coronal and transverse plane force couples (Figure 1.2 and Figure 1.3). In the coronal plane, the deltoid imposes a superiorly and medially directed force on the humerus. However, the infraspinatus, subscapularis and teres minor impose inferiorly and medially directed forces on the humerus (9). If the superiorly and inferiorly directed forces are balanced the humerus will remain centered on the glenoid in the superior-inferior direction. On the other hand, if the coronal plane force couple is not balanced and the deltoid force is greater, superior migration may occur resulting in compression of the rotator cuff tendons on the undersurface of the acromion. In the transverse plane, the subscapularis imposes a medially and anteriorly directed force on the humerus and the infraspinatus and teres minor impose medially and posteriorly directed forces on the humerus (10, 11). If the transverse plane force couple is balanced the humerus will remain centered in the anterior-posterior direction.

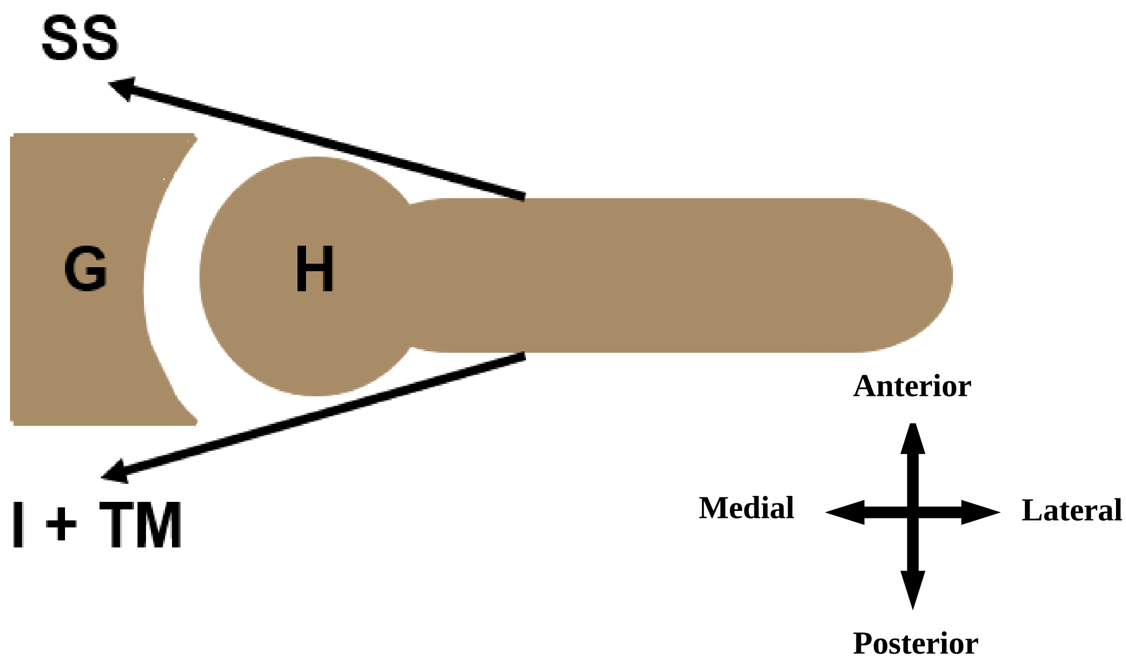

Figure 1.2: Depiction of the muscle forces comprising the transverse plane force couple (SS, Subscapularis; I, Infraspinatus; TM, Teres Minor; H, Humerus; G, Glenoid).

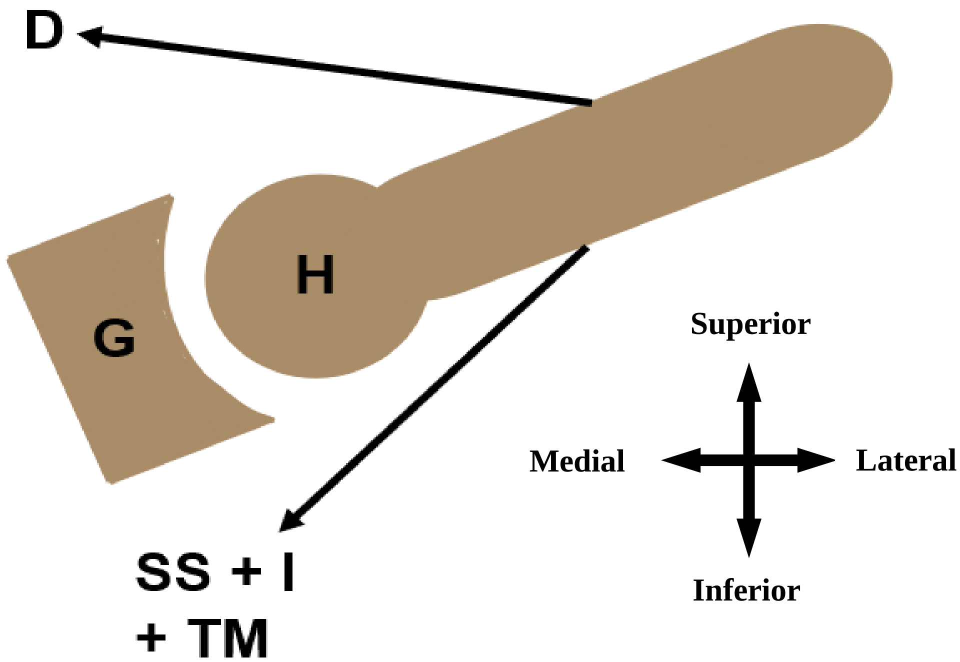

Figure 1.3: Depiction of the muscle forces comprising the coronal plane force couple (D, Deltoid; SS, Subscapularis; I, Infraspinatus; TM, Teres Minor; H, Humerus; G, Glenoid).

1.2 Rotator Cuff Tears

Rotator cuff tears most commonly occur in the supraspinatus tendon but may originate in other tendons of the rotator cuff tear. The injury is generally atraumatic occurring overtime where the tendon is damaged due to repetitive motions over one's lifetime but may also occur due to a traumatic event. If not treated appropriately, the tear may propagate into a larger tear resulting in worse pain and loss of function. The cause of rotator cuff tears is difficult to pinpoint as many factors play a role including mechanical trauma, underlying biological mechanisms, a history of smoking, age and many other factors (12-14). Mechanically speaking, a common theory for the development of rotator cuff tears is subacromial impingement (15, 16). Subacromial impingement is defined as a narrowing of the space below the acromion process, resulting in compression on the rotator cuff tendons and potentially microtrauma leading to a tear.

Extrinsic mechanisms of rotator cuff tears are thought to include both biomechanical and anatomical factors. For example, the shape of the acromion has been shown to relate with the severity of the tear (17), where the shape is generally defined as one of three types: 1) flat, 2) curved and 3) hooked (18). Biomechanically, decreased rotator cuff muscle function or abnormal scapular kinematics may lead to superior humeral head migration causing dynamic narrowing of the subacromial space compressing the rotator cuff tendons (17, 19).

Individuals with a rotator cuff tear isolated to the supraspinatus tendon generally maintain sufficient function where both cadaveric and human subject research have demonstrated that loss of function most likely occurs when the tear propagates to a neighboring tendon (20). Specifically, the intact rotator cuff is capable of maintaining the coronal and transverse plane force couples as long as the tear remains isolated to the supraspinatus tendon (21). If the isolated tear propagates to the neighboring tendons (e.g., infraspinatus), the force couples are disrupted and abnormal glenohumeral joint function is observed. Studies have shown that the magnitude of the glenohumeral joint reaction force is reduced when the tear propagates to neighboring tendons (20). Additionally, as the tear grows larger, individuals generally experience significant pain and loss of function (22). Therefore, proper clinical decision making is required to ensure initial treatment methods address any abnormalities in joint function that may lead to the injury worsening and becoming more difficult to treat.

1.2.1 Altered Glenohumeral Joint Function

Due to the importance of the rotator cuff for maintaining joint stability, many studies have investigated the effects of rotator cuff tears on joint function. The main outcome parameters usually investigated are glenohumeral kinematics and arthrokinematics, specifically rotations, translations and contact path lengths (the amount of movement of the humeral head on the surface of the glenoid) as they provide insight on joint function. If the magnitude of the glenohumeral translations or contact path length increases, that may indicate the rotator cuff is not properly stabilizing the humeral head on the glenoid surface.

Furthermore, computational modeling and cadaveric studies investigate changes in the magnitude and direction of the glenohumeral joint reaction force (20, 23, 24). If the magnitude of the glenohumeral joint reaction force decreases, the rotator cuff may not be producing sufficient force to maintain concavity compression. The direction of the glenohumeral joint reaction force then provides information on the efficacy of the glenohumeral force couples to center the humeral head on the glenoid. Ideally, the joint reaction force will be within the glenoid depicted by the dashed lines in Figure 1.4. If the direction is less centered in the glenoid, proper joint function may not be possible.

In-vivo studies investigating glenohumeral kinematics have demonstrated less posterior tilting of the scapula and less glenohumeral external rotation during scapular plane abduction in individuals with symptomatic rotator cuff tears compared to healthy and asymptomatic individuals (25). Furthermore, cadaveric studies demonstrated no differences in the magnitude of the joint reaction force between intact, isolated incomplete supraspinatus tendon tears, or complete supraspinatus tendon tears. However, extension of the tears beyond the supraspinatus led to significant decreases in the magnitude of the joint reaction force (20). Additionally, extension of the tears beyond the supraspinatus led to changes in the direction of the joint reaction force. Computational modeling studies have also shown differences in the magnitude of the joint reaction force during pulling and axilla wash movements between individuals with rotator cuff tears and controls (23).

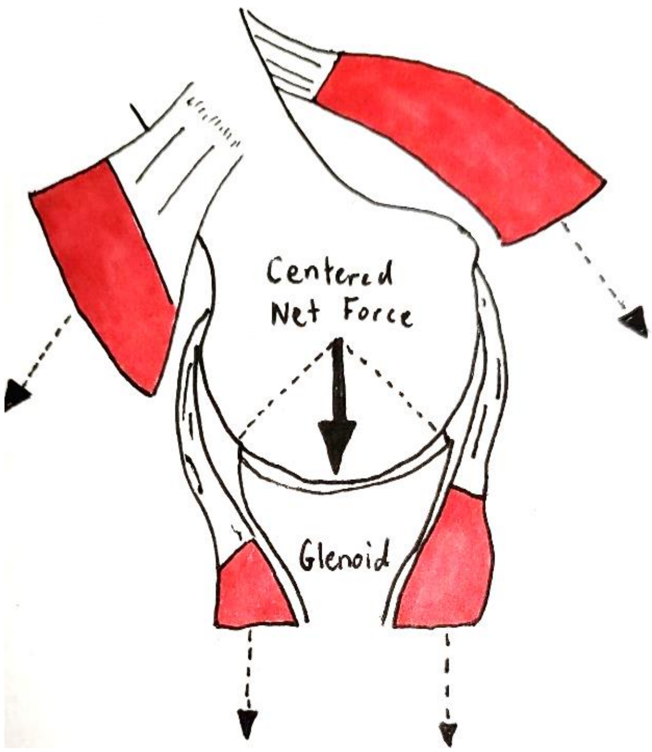

Figure 1.4: Rotator cuff and deltoid muscle forces (dashed arrows) maintain the net joint reaction force (solid arrow) within the glenoid.

1.2.2 Considerations for Initial Treatment of Rotator Cuff Tears

Although many factors are related to pain and loss of function experienced by individuals with rotator cuff tears, there are three primary factors considered when determining initial treatment. These factors include: 1) tear size, location and propagation, 2) pain and 3) function. Given rotator cuff tears most commonly occur in the supraspinatus tendon, the information provided here is in respect to isolated supraspinatus tears but can generally be applied to a rotator cuff tear that includes the other tendons. Generally, rotator cuff tears are diagnosed using magnetic resonance imaging or ultrasound as both methods are not invasive and induce no radiation. An example of measuring tear size using ultrasound is shown in Figure 1.5. Tear location may be defined as the distance from the posterior edge of the long head of the biceps to the most anterior edge of the tear (21). The larger the tear is, the more likely a surgeon will recommend surgery. The rationale for this recommendation is that if the tear were to propagate, repairing the torn tendon becomes more difficult with a higher chance of worse outcomes. Thus, surgeons generally believe that surgical treatment will predictably prevent the tear from propagating (26, 27).

However, others believe that exercise therapy helps strengthen the intact rotator cuff and rebalance the force couples necessary to maintain glenohumeral joint stability (28). Cadaveric studies have also shown that tears in the anterior portion of the supraspinatus propagate at lower loads (29). Understanding the effects exercise therapy has on tear propagation will provide information to clinicians on the likelihood the tear will worsen if exercise therapy is prescribed for initial treatment. Pain and function are also important factors to consider when determining initial treatment. Exercise therapy is usually successful in relieving pain, restoring normal range of motion, and strengthening the rotator cuff and scapular stabilizing muscles (30-33). However, some individuals may experience more pain and loss of function and prefer to undergo surgery.

This decision may also be influenced on the individual's perception on the success of exercise therapy, where those who do not believe exercise therapy will be beneficial have worse outcomes (34). If an individual only has minor limitations in joint function, exercise therapy may be a more beneficial option as it is less invasive, however, more high level evidence is needed in general to support the optimal initial treatment plans. Specific examples of study designs capable of generating high level evidence include Randomized Controlled Trials or Prospective Cohort Studies.

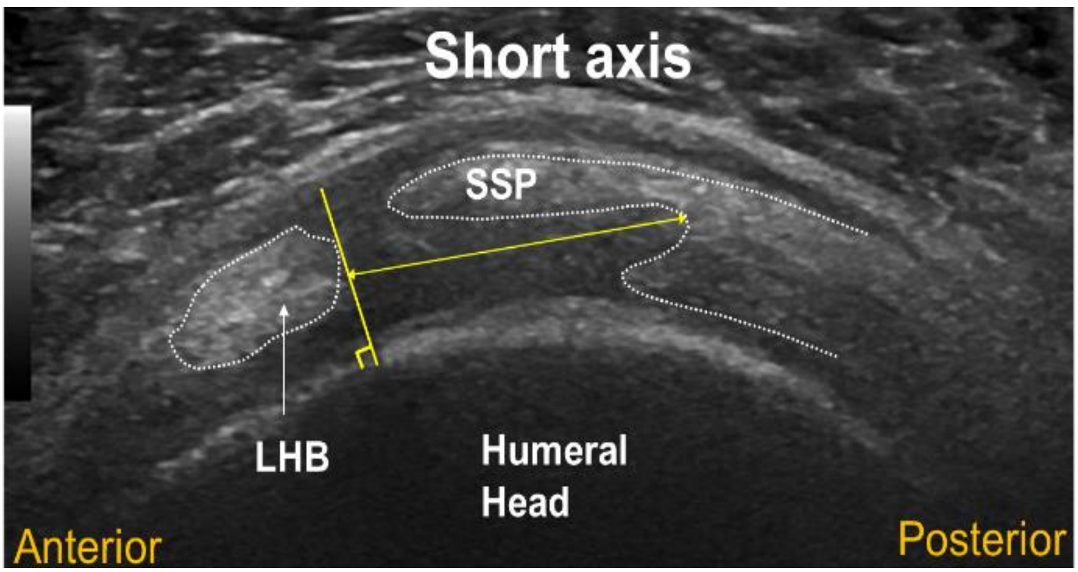

Figure 1.5: Example AP tear size measurement on short-axis image with a tear location of 0.0mm (Long Head of the Biceps (LHB), Supraspinatus (SSP)).

1.2.3 Methods of Quantifying In-Vivo Kinematics

The kinematics of the shoulder complex have been investigated for many years and quantified utilizing various static and dynamic techniques. The most accurate dynamic in-vivo methods include biplane radiography and fluoroscopy. Biplane radiography systems are comprised of two pulsed x-ray generators and image intensifiers where image acquisition is synchronized during dynamic movements. The systems are generally constructed in a movable framework which allows manipulation of the systems generators and intensifiers to optimize image acquisition depending on the movement being performed (35). The glenohumeral joint is centered within the system to ensure the joint/side of interest is within the field of vision of the system and images are usually acquired at 50 images/second depending on the speed of the movement. Measurement accuracy for translations and rotations of the glenohumeral joint are ± 0.4mm and ± 0.5°, respectively when using validated model based tracking methods (35). Generally, biplane fluoroscopy systems can be modified to perform similarly and have similar accuracy (36), but usually have lower capture rates and longer pulse widths. Lower capture rates will limit what movements can be imaged and longer pulse widths will expose the individual to additional radiation.

Glenohumeral kinematics in the current dissertation were all determined using biplane radiography and a previously described model-based tracking technique (35). Briefly, subject specific bone models of the humerus and scapula were created from computed tomography images and matched to the synchronized biplane radiographs collected during the movement. Once the humerus and scapula have both been tracked in all images and views, it is possible to derive glenohumeral kinematics. The method just described has been used in numerous studies quantifying glenohumeral joint function, but generally included more simplistic movements such as abduction and internal-external rotation with the arm by the side (21, 31-33, 37, 38).

1.2.4 Glenohumeral Joint Function

Joint function has been investigated using the previously described in-vivo techniques following exercise therapy, rotator cuff repair, and in asymptomatic or healthy control groups. Changes in joint function following exercise therapy in individuals with rotator cuff tears have been variable with some conflicting evidence. A study including five individuals that underwent a 12-week exercise therapy program found decreased contact path lengths (Figure 1.6) and no changes in superior-inferior contact center ranges, whereas increased superior-inferior contact center ranges during coronal plane abduction were observed in 25 individuals following exercise therapy (31, 33). Additional conflicting results were reported since no changes in contact path length were observed following exercise therapy in the cohort of 25 individuals, however, the exercise therapy program was only 8 weeks long (33). In five individuals with rotator cuff tears, no changes in joint function were also observed following exercise therapy during an internal-external rotation movement with the arm by the side, potentially indicating changes in joint function are movement dependent (32). Exercise therapy protocols may also need to be modified to better target movements where improvements in joint function were not observed.

Joint function following rotator cuff repair and dynamic elongation of rotator cuff repairs have been investigated using biplane radiography (37, 38). Individuals with rotator cuff tears underwent in-vivo kinematic testing at 3, 12 and 24 months following surgical repair of a torn supraspinatus tendon. Kinematics were compared to controls with no identified pathology of the rotator cuff. Individuals that underwent surgery had humeri that were more superiorly positioned on the glenoid compared to the contralateral side and the dominant side of controls. No changes in glenohumeral joint kinematics were observed over time, indicating current repair techniques may not fully restore joint function (37). Another study investigated the subacromial space during abduction following rotator cuff repair. Subacromial space became smaller with increasing abduction but was only 0.5mm less than the contralateral asymptomatic shoulder from 10-60° of glenohumeral abduction (39). A more recent paper investigated how the repaired rotator cuff tissue functions under dynamic movement. A 3.1mm bead capable of being visualized on biplane radiographs was sutured to the supraspinatus tendon. Kinematic testing occurred at 1 week and 3 months after the time of surgery. During scapular plane abduction, maximum elongation averaged 1.4 ± 1.0mm (38).

In-vivo glenohumeral kinematics have also been determined in healthy controls and asymptomatic individuals. The effect of the plane of elevation was investigated in healthy controls where scapulohumeral rhythm and glenohumeral translations were quantified during coronal plane abduction, scapular plane abduction and forward flexion. Humeral head translations were largest in coronal plane abduction and scapulohumeral rhythm decreased moving from the coronal plane to the sagittal plane (40). Another study compared various kinematic parameters in healthy controls to individuals with asymptomatic and symptomatic rotator cuff tears confirmed via magnetic resonance imaging (25). During scapular plane abduction, individuals with symptomatic rotator cuff tears had less scapular posterior tilt compared to healthy controls and the humerus was less externally rotated compared to both asymptomatic and control individuals. Interestingly, asymptomatic individuals have also been shown to have longer contact path lengths, less strength and a more inferiorly oriented humerus compared to healthy controls suggesting a possible mechanistic progression leading to pathology of the cuff (41).

Due to conflicting results during simple abduction movements and indications that improvements are movement dependent following exercise therapy, joint function should be investigated in a large cohort with a well-defined exercise therapy program and include more complex movements. An example of a more complex movement includes reaching behind the back, which is important for activities of daily living including reaching into the front and back pocket or performing personal hygiene. Individuals with rotator cuff tears also commonly experience pain during this movement, which may be due to the position maximally stretching the supraspinatus inducing pain originating from the tear (42). Reaching behind the back has been investigated in individuals with no rotator cuff pathology (43-45), but relative changes in joint function during this movement should be defined in individuals with rotator cuff tears following exercise therapy.

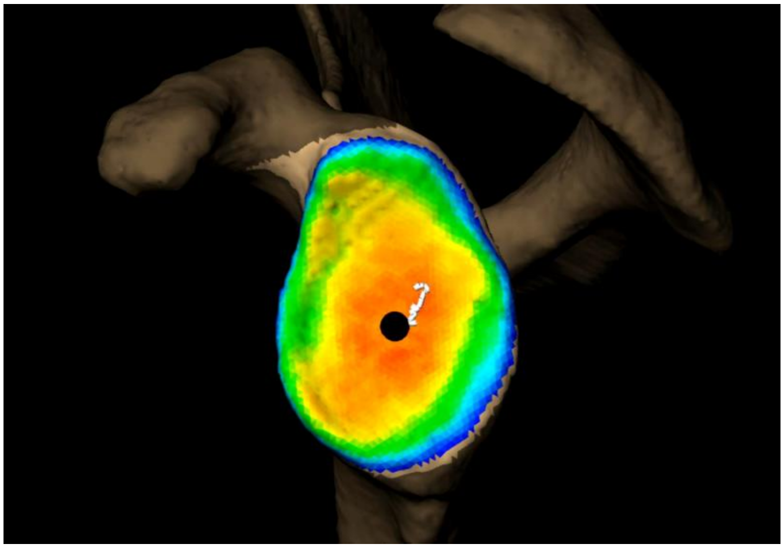

Figure 1.6: Example of contact path in an individual with an isolated supraspinatus tear post-exercise therapy during scapular plane abduction. The white line represents the contact path, the color map represents the distances between the points on the humerus and scapula and the black dot represents the contact center.

1.3 Musculoskeletal Computational Models

As previously mentioned, the magnitude and direction of the glenohumeral joint reaction force are important parameters that provide information on joint stability. However, these parameters cannot be measured in-vivo unless an instrumented implant is surgically implemented. In the case of individuals with symptomatic isolated supraspinatus tears, instrumented implants would not be prescribed, thus alternative methods are required to estimate the magnitude and direction of the glenohumeral joint reaction force. Computational models are commonly employed to estimate the magnitude and direction of the joint reaction force in healthy individuals and individuals with rotator cuff tears.

Computational models of the musculoskeletal system are commonly constructed using OpenSim, an open source software utilized to develop biomechanical models and perform various simulations and analyses regarding joint function (46). Briefly, bone models can be imported and scaled using anthropometric data to represent the respective subject. Alternatively, subject specific bony geometries can also be imported to more accurately represent the subject being modeled. Muscle-tendon units can also be implemented where the origins and insertions of the respective muscle are geometrically defined, and parameters are provided to describe the muscles' function. Subject specific kinematic and electromyography data can also be employed to drive simulations or validate models.

The two main workflows utilized in OpenSim are the inverse and forward simulations. For the purpose of the current work, the inverse workflow will be utilized and thus, it will be discussed here. Inverse workflows utilize experimental kinematics as the main input which are used to estimate or predict joint moments, muscle forces and joint reaction forces. In the simplest case, an inverse simulation would utilize experimentally collected kinematics to drive the model and an extension to inverse dynamics, called static optimization, would be used to determine the muscle forces required to produce the observed kinematics. Following static optimization, joint reaction force analysis is used to determine the joint reaction forces produced by the joint of interest. An example of a model created in OpenSim that will be utilized for the analyses included in the current dissertation is shown in Figure 1.7. The red units represent the rotator cuff and middle deltoid muscles, in the form of lines of action.

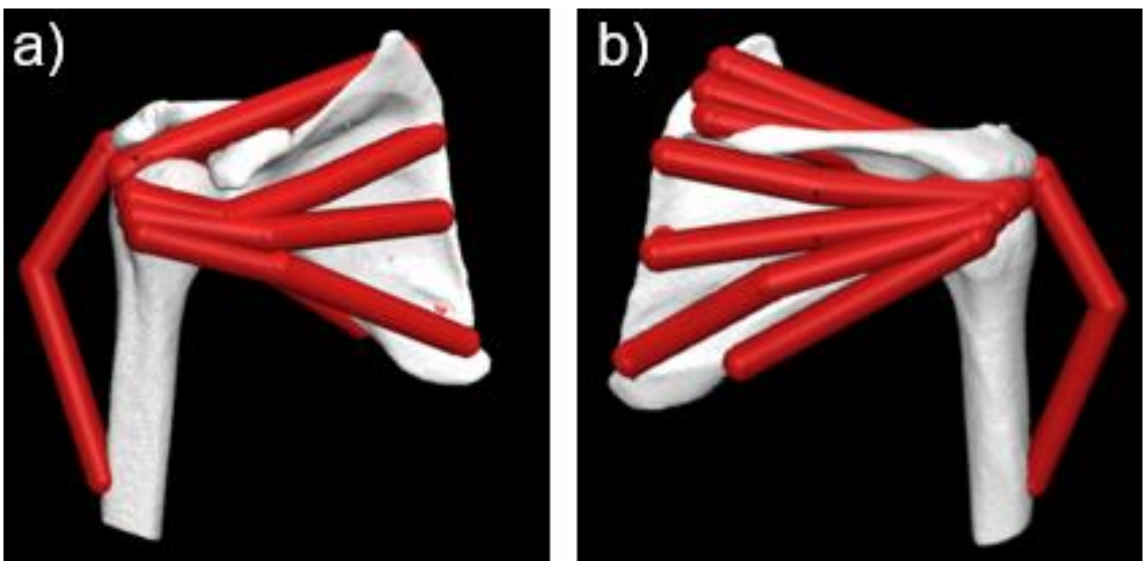

Figure 1.7: Example of a subject specific model of the glenohumeral joint. Image a) is an anterior view showing the subscapularis (represented with three units), the middle deltoid and the supraspinatus (modeled with 3 units). Image b) is a posterior view showing the infraspinatus (modeled with 3 units), the teres minor, the supraspintus and the middle deltoid.

1.3.1 Previous Computational Models of the Shoulder Complex

Some of the earliest work conducted on computational models for the shoulder complex investigated the kinematic and dynamic behavior of the shoulder (47, 48). The model consisted of 20 muscles, three joints (scapulothoracic, acromioclavicular and glenohumeral), three extracapsular ligaments and various constraints involving scapular motion and maintenance of the humerus within the glenoid. Surface elements were developed to represent motion of the scapula in respect to the thorax and curved-truss elements to represent muscles wrapping around bone (48). Extensive analyses were conducted to validate and describe the model's behavior including predicted motion, muscle forces, muscle lengths and comparisons with electromyography data. The magnitude and direction of the joint reaction forces were also determined.

More recent computational models are readily accessible thanks to the open-source nature of tools like OpenSim and have been used to predict function in individuals with rotator cuff tears. An example of a readily available model is the MoBL-ARMS Dynamic Upper Limb model which has been used to investigate glenohumeral joint function (49, 50). During a pull and axilla washing movement, differences in the peak joint reaction force were observed using computational models between healthy individuals and individuals with rotator cuff tears (23). The models included 50 muscle-tendon units representing 32 muscles crossing the shoulder, elbow, forearm and wrist and utilized kinematics derived from motion capture. The referenced study also demonstrated individualized muscle forces used as inputs in the model influenced the observed results demonstrating a need to individualize the maximum force each muscle can produce during the simulated movements. Individualized muscle forces were determined using muscle volume segmented using magnetic resonance imaging. Significant work has also been performed to characterize muscle volume and strength in older individuals, individuals with rotator cuff tears and even the effects of resistance training on muscle volume as the information can be used to scale and individualize computational models (51-57).

Magnitude and direction of the glenohumeral joint reaction force has also been shown to change with increasing tear severity (24). Specifically, during various tasks the magnitude decreased by approximately 10.0% with infraspinatus involvement and approximately 21.0% with subscapularis involvement compared to models with "no tear." The direction of the joint reaction force also pointed more inferiorly with greater tear severity, indicating the contact force pointed more superiorly. The implication of these results may be a greater likelihood of superior humeral head migration and decreased concavity compression.

Previous studies have also demonstrated the importance of developing methods to quantify and investigate fatty infiltration, especially in the case of pathology such as individuals with rotator cuff tears (55, 58). An important finding was that fatty infiltration percentages were greater by approximately 2.0-4.0% depending on the muscle in individuals with an isolated supraspinatus tendon tear compared to controls (55). Thus, it may be important to incorporate fatty infiltration into computational models utilizing muscle volume as a subject specific input given the entire muscle may not be able to generate force.

Additional models utilized to investigate some aspect of the shoulder complex include the Scapulothoracic Joint Model, Dynamic Arm Simulator and Delft Shoulder and Elbow Model (59-62). Models such as the Delft Shoulder and Elbow Model have been used for a variety of applications such as tendon transfers, wheelchair propulsion and development of neuro-prostheses (63-65). Computational modeling has also been used to investigate brachial plexus injuries, and the effects on the glenohumeral joint (66-75). Additional injuries such as rotator cuff tears and nerve injury have been investigated, along with surgical procedures such as tendon transfers and rotator cuff repair (23, 76-82). Furthermore, crucial analyses have been conducted to determine in-vivo muscle parameters and sensitivity or usability analyses of computational models in respect to parameters such as muscle moment arms and stability modeling approaches (83-88). Associations between joint function and patient reported outcomes, as well as more unique situations such as incorporation of reinforcement learning, statistical parametric mapping or wearable shoulder exoskeletons have also been investigated (89-92).

Overall, each model has their own strengths and weaknesses, and provides options for researchers to predict various parameters related to joint function during different activities. Although all the previously developed models prove to be useful tools, they may not be constructed in a manner that allows one to answer any research question appropriately. For example, many models determine the orientation of the scapula using regression equations based on the motion of the humerus (23, 62). This specific modeling choice may be satisfactory for healthy individuals, but it will not be representative of individuals with pathologic related changes in scapulothoracic motion. Regarding the initial treatment of rotator cuff tears, understanding changes in the magnitude and direction of the glenohumeral joint reaction force following exercise therapy will provide information on how exercise therapy influences joint stability.

Due to improvements in muscle strength following exercise therapy, one would expect to see increases in the magnitude of the joint reaction force that also centers the humeral head on the glenoid. To perform such analyses, a developed model will need to accurately represent glenohumeral joint kinematics and model the necessary structures appropriately. Furthermore, the model could then be used to compare individuals who eventually underwent surgery versus those that did not which may provide motivation to alter current treatment modalities or increase the number of treatment sessions. This novel information could then be applied to future studies to determine if individuals that do not respond to 12-weeks of exercise therapy improve following additional treatment sessions. In the current dissertation, subject specific models were created to investigate the proposed research questions.

1.3.2 Validation of Computational Models

Determining whether newly developed models produce reasonable results is a key step in the developmental process and generally requires multiple validation steps utilizing different data elements (internal and external data sets). Furthermore, the specific validation criteria utilized will depend on the model and proposed research questions. For example, if the joint reaction force is the main outcome parameter of interest, the simulated results should be compared to previous experimental studies utilizing cadavers, in-vivo instrumented implants and computational models (93). Examples of validation steps from previous literature include comparing electromyography data to activation results obtained from simulations, comparing simulated muscle moment arms to previous experimental cadaveric studies, comparison of predicted joint reaction forces to instrumented implant results and comparison of experimental and simulated kinematics (23, 47, 61, 93). In the current dissertation, four different validation criteria were established, and analyses were performed to determine if the developed models were appropriate to answer the proposed research questions.

2.0 Motivation

Rotator cuff disease continues to be a highly important clinical problem due to the lack of high-level evidence supporting the optimal method for initial treatment (exercise therapy vs. surgery). The prevalence of rotator cuff tears increases with age and ranges from 10.7% to 36.6% of individuals between the ages of 50 to 80 years old, with a high incidence of tears in both shoulders (94-100). Due to medical advances, 20.0% of individuals are projected to be 65 years of age or older by the year 2030 (101), highlighting the importance of determining the most effective initial treatment for individuals with rotator cuff tears since prevalence increases with age. The ability of rotator cuff tears to significantly impact quality of life and productivity underscores the importance of timely and effective treatment before the tear can substantially propagate to become a large or massive tear, which is more difficult to surgically repair and is associated with worse clinical outcomes (102-105). Approximately 3-5 billion dollars in treatment costs are associated with treatment of rotator cuff tears and 4.5 million physician visits occur yearly for rotator cuff pathology (106-108). Thus, due to the high incidence of rotator cuff tears and cost of treatment, determining the optimal method for initial treatment of rotator cuff tears is essential.

Both exercise therapy and surgical treatment have unsatisfactory failure rates, where exercise therapy fails in approximately 25.0-50.0% of cases (30, 109-113) and primary surgical treatment fails in approximately 20.0-69.0% of cases (114, 115). Understanding key factors related to the success or failure of exercise therapy is important given this modality is commonly prescribed for initial treatment. If exercise therapy fails, individuals undergo surgery extending the duration of their functional deficits and pain, and further increases economic burden on the individual and healthcare system. Overall, factors that are important to investigate include characterization of individuals pain, function and tear size before exercise therapy, as well as relative changes in joint function, tear size, and patient reported outcomes after exercise therapy.

Minimal information is available regarding the effects of exercise therapy on rotator cuff tear size. Investigating if exercise therapy increases the risk of tear propagation will allow clinicians to make more informed decisions on initial treatment and whether individuals that do not respond to exercise therapy also experience tear propagation. The likelihood of tear propagation may also be linked to abnormal glenohumeral arthrokinematics and unbalanced glenohumeral joint force couples. Individuals that do not respond to the prescribed exercises may have imbalances which leads to increased forces applied to the torn tendon. Increased forces may then lead to tear propagation and lead to worse outcomes.

Uncovering differences in joint function using computational models between individuals that eventually underwent surgery and individuals that did not may elucidate important factors related to treatment outcomes. If differences in the magnitude and direction of the joint reaction force exist between the two groups, new targetable factors during treatment will be elucidated. The implications of these findings could provide support for alterations to current treatment methodologies or additional exercise therapy sessions for individuals that do not respond to 12-weeks of exercise therapy. Furthermore, models could be created for individuals diagnosed with rotator cuff tears and used as a clinical tool to guide long-term treatment.

Thus, developing a better understanding of the effects of exercise therapy for initial treatment of individuals with symptomatic isolated supraspinatus tears may improve treatment modalities, improve long-term outcomes and influence the future of health care policy. Regarding health care policy, the current work may help choose the optimal treatment for individuals from the start avoiding the high costs associated with failed treatments, ultimately benefiting the individual and society. Clinicians will be able to utilize the results of this dissertation to make more informed decisions for initial treatment, understand the risks for tear propagation and changes in joint function that occur following exercise therapy. Furthermore, the current dissertation will provide information that may improve current treatment protocols and evaluate the number of individuals from a large and unique cohort who underwent surgery at 2-year follow-up. Long-term follow-up data will also enable clinicians to provide important information for patients to consider when deciding a treatment pathway.

2.1 Specific Aims

The overall objective of this dissertation was to characterize a large cohort of individuals with symptomatic rotator cuff tears isolated to the supraspinatus tendon and determine the changes in functional and clinical parameters following exercise therapy. To characterize a large cohort and determine changes following exercise therapy, three specific aims were accomplished:

2.1.1 Specific Aim 1

Characterize the baseline presentation of individuals with symptomatic isolated supraspinatus tears and the relationships between range of motion, muscle strength, tear size, patient reported outcomes and glenohumeral kinematics before a 12-week structured exercise therapy program.

Hypothesis 1a: Passive range of motion and muscle strength will negatively correlate with glenohumeral translations and contact path length during scapular plane abduction.

Hypothesis 1b: Glenohumeral translations and contact path length during scapular plane abduction will negatively correlate with patient reported outcomes.

Hypothesis 1c: Tear size will be positively associated with glenohumeral translations and contact path length during scapular plane abduction.

2.1.2 Specific Aim 2

Assess changes in glenohumeral joint function, patient reported outcomes and tear size following a 12-week personalized exercise therapy program.

Hypothesis 2a: Contact path lengths during scapular plane abduction and when reaching behind the back will decrease post-exercise therapy.

Hypothesis 2b: Maximum glenohumeral abduction and internal rotation will increase post-exercise therapy during scapular plane abduction and when reaching behind the back, respectively.

Hypothesis 2c: Patient reported outcomes, isometric muscle strength and passive glenohumeral range of motion will increase, and no tear propagation will occur post-exercise therapy.

Hypothesis 2d: Changes in glenohumeral joint function will be associated with improvements in patient reported outcomes.

2.1.3 Specific Aim 3

Assess changes in joint stability following a 12-week personalized exercise therapy program using subject specific models. Comparisons between individuals who had a successful vs. unsuccessful outcome following exercise therapy will be made to elucidate characteristics of individuals that did not respond to exercise therapy.

Exercise therapy was considered successful if the individual did not undergo surgical treatment within 2-year follow-up and was considered to be unsuccessful if the individual underwent surgical treatment for the rotator cuff tear within 2-year follow-up.

Hypothesis 3a: Individuals who had an unsuccessful outcome following exercise therapy will have lower magnitudes of the joint reaction force compared to individuals successfully treated with exercise therapy.

Hypothesis 3b: The direction of the magnitude of the joint reaction force will be less centered on the glenoid in individuals who had an unsuccessful outcome following exercise therapy compared to individuals successfully treated with exercise therapy.

3.0 Aim 1: Characterizing the Baseline Presentation of Individuals with Rotator Cuff Tears

The following article was published in the Journal of Shoulder and Elbow Surgery, Volume 31, Luke T. Mattar, Adam J. Popchak, William J. Anderst, Volker Musahl, James J. Irrgang, Richard E. Debski, Associations Between Range of Motion, Strength, Tear Size, Patient Reported Outcomes, and Glenohumeral Kinematics in Individuals with Symptomatic Isolated Supraspinatus Tears, Pages 1261-1271, Copyright Journal of Shoulder and Elbow Surgery Board of Trustees (2022) (21).

3.1 Associations Between Range of Motion, Strength, Tear Size, Patient Reported Outcomes, and Glenohumeral Kinematics in Individuals with Symptomatic Isolated Supraspinatus Tears

3.1.1 Introduction

The incidence of rotator cuff tears in the general population is approximately 30%, with prevalence increasing in those above the age of 60 (12). Non-operative treatment, rather than surgical repair, is the initial treatment choice for rotator cuff tears and focuses on reducing pain, restoring normal range of motion, and strengthening the rotator cuff and scapular stabilizing muscles (30, 109-113, 116). While non-operative treatment is often effective for relieving symptoms, it fails in 15-68% of cases necessitating surgical intervention (117, 118). Failure rates associated with non-operative treatment may be due to varying treatment protocols or inadequate characterization of impaired function in individuals with rotator cuff tears used to determine the specific treatment for individual patients (119).

Common impairments associated with rotator cuff tears seen clinically include decreased passive range of motion (ROM) and rotator cuff muscle strength (41, 120). Mechanistically, it has been hypothesized that decreased passive glenohumeral internal rotation and abduction ROM (restrictions are considered to imply posterior and inferior capsular tightness) and decreased rotator cuff muscle strength disrupting the coronal and transverse plane force couples (subscapularis, infraspinatus, and teres minor) relates to altered glenohumeral translations and less joint stability (120, 121). To improve the success of non-operative treatment of supraspinatus tears, a better understanding of the aforementioned impairments prior to non-operative treatment is necessary as they may provide further insight on the individual's impaired function and direct specifics of non-operative treatment.

Previous studies utilizing cadavers and static in-vivo radiographic images assessed glenohumeral translations in the presence of rotator cuff tears and observed superior migration of the humeral head (122-126), where it is generally believed that superior migration worsens with increasing tear size (126, 127). However, conflicting results reported inferior glenohumeral translations in individuals with rotator cuff tears isolated to the supraspinatus during scapular plane abduction measured with biplane fluoroscopy (36). Furthermore, experimentally induced capsular contractures have been shown to increase anterior and superior glenohumeral translations (120, 121). This phenomenon was termed the "capsular constraint mechanism" in which the humeral head translates away from the tightened portion of the capsule (121, 128). In the clinical setting, both superior migration with increasing tear size and the effects of capsular tightness are widely acknowledged in individuals with rotator cuff tears. Although the effects of capsular tightness are well described in cadavers, little data exists regarding the effects of capsular tightness on glenohumeral kinematics in-vivo in individuals with isolated supraspinatus tendon tears prior to exercise therapy. Specifically, the demographic and clinical factors (i.e. strength, ROM, atrophy, tendon involvement) relating to patient reported outcomes have been investigated in individuals with symptomatic atraumatic rotator cuff tears prior to initiation of a physical therapy program, but did not investigate glenohumeral kinematics (129). Furthermore, the relative changes in a combination of variables such as passive and active ROM, strength, PROs, and in-vivo glenohumeral kinematics have been described following a physical therapy program (30, 31, 33). However, these previous studies only looked at relative changes and did not determine the time-zero relationship between factors such as passive ROM and glenohumeral kinematics.

Furthermore, little is known regarding the effects of tear size on muscle strength. A previous study investigated the association between abduction, internal, and external rotation muscle strength and presence of a supraspinatus tear and found that decreased abduction and external rotation strength were associated with supraspinatus tears (130). Mechanistically, larger tears may further disrupt the glenohumeral force couples and influence rotator cuff muscle strength and contact path length. Thus, understanding whether or not rotator cuff muscle strength decreases and contact path length increases with increasing tear size will elucidate if some individuals enter exercise therapy with greater impairments. This information will also aid in directing specifics of future exercise therapy programs.

Thus, little data exists regarding the relationships between passive glenohumeral ROM, rotator cuff muscle strength, tear size and glenohumeral kinematics in a population of individuals with an isolated supraspinatus tear prior to initiation of non-operative treatment. Additionally, patient reported outcomes are commonly collected to gain insight on an individual’s perceived pain and function. Thus, if individuals experience larger glenohumeral translations and contact path lengths, which indicate worse control of the humeral head, it may relate to worse patient reported function. Understanding the relationship between glenohumeral kinematics and patient reported outcomes (PROs) may elucidate if changes in glenohumeral function affect an individual's perception of their pain and function prior to exercise therapy.

Therefore, the overall objectives of the study were to describe the clinical presentation of individuals with a symptomatic isolated supraspinatus tear and determine if common clinical measures of function in individuals with rotator cuff tears relate to in-vivo glenohumeral kinematics. Clinical measures of function used to describe initial presentation, as well as associations with glenohumeral kinematics, included passive glenohumeral ROM, isometric muscle strength, PROs, and tear size. Specific objectives of this study were the following: 1) Describe the clinical presentation of individuals with a symptomatic isolated supraspinatus tear, 2) determine the relationships between passive glenohumeral ROM, isometric rotator cuff muscle strength, tear size and glenohumeral kinematics, and 3) determine the relationships between glenohumeral kinematics and PROs (American Shoulder and Elbow Surgeons Score, ASES; Western Ontario Rotator Cuff Index, WORC). Achieving these objectives will identify impairments, as well as links between impairments and underlying joint mechanics, in individuals with symptomatic rotator cuff tears isolated to the supraspinatus tendon prior to initiation of non-operative treatment.

It was hypothesized that: 1) Internal and external rotation strength will be negatively correlated with maximum superior glenohumeral translations and contact path length, 2) tear size will be negatively associated with internal and external rotation strength and positively associated with glenohumeral contact path length, 3) clinically assessed glenohumeral internal rotation, glenohumeral abduction, and glenohumeral flexion will be negatively correlated with maximum superior and anterior glenohumeral translations, 4) maximum glenohumeral anterior and superior translations and contact path length will be negatively correlated with PROs (Figure 3.1).

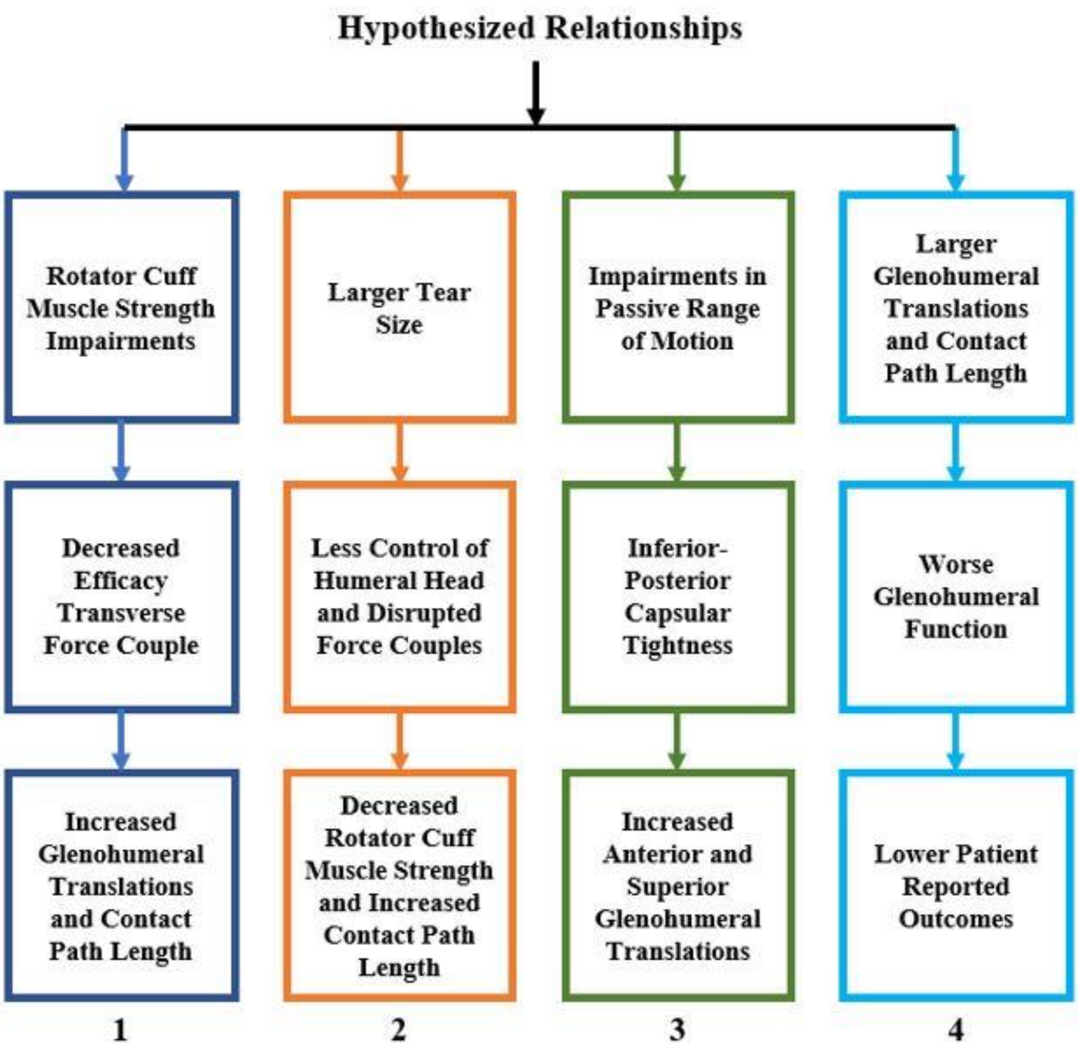

Figure 3.1: Rationale flowchart for hypothesized relationships.

3.1.2 Materials and Methods

One-hundred one individuals (mean age 60.6 ± 9.7 years, mean BMI 28.8 ± 4.9) were recruited to participate in the study and provided IRB-approved written informed consent prior to performance of any research procedure. One-hundred one of the 109 individuals in the cohort were utilized based upon the available and useable in-vivo kinematic data. Individuals were eligible to enter the study if they: 1) were above the age of 40 years; 2) had BMI less than 40; 3) had a partial- or full-thickness rotator cuff tear isolated to the supraspinatus tendon (confirmed via ultrasound screening of the rotator cuff tendons); 4) had at least 110° range of humerothoracic elevation. Individuals were excluded if they had a work-related injury, had an asymptomatic rotator cuff tear, had severe capsular tightness as evidenced by less than 30° of internal or external rotation, duration of shoulder pain exceeding 12 months, or had diabetes mellitus.

Passive glenohumeral ROM and isometric strength of the rotator cuff muscles were measured by one of three certified and experienced physical therapists at the Physical Therapy-Clinical and Translational Research Center in the Department of Physical Therapy at the University of Pittsburgh. For each individual, passive glenohumeral abduction, flexion, and internal rotation at 90° of humerothoracic abduction were assessed using a goniometer. Individuals were in supine position for all passive ROM assessments. The amount of glenohumeral abduction and flexion was determined by palpating the lateral border of the scapula while moving the humerus in the coronal and sagittal planes, respectively. When the physical therapist felt the scapula upwardly rotate, the motion was stopped, and the measurement was recorded. Internal rotation was measured at 90° of humerothoracic abduction in the coronal plane with the elbow at 90° of flexion. The motion was stopped, and the measurement was recorded when the scapula began to tilt anteriorly. These passive ROM measurements were recorded once and were chosen as they assess inferior and posterior capsular tightness, as well as glenohumeral joint function. Previous literature assessing isolated glenohumeral ROM in healthy individuals has demonstrated intra- and inter-observer repeatability ranging from 0.62 to 0.84 and 0.62 to 0.86, respectively, for various joint positions (131).

Isometric strength measurements were taken as previously described (31, 32) using a handheld dynamometer (Lafayette Manual Muscle Testing System, Lafayette Instrument Company, Lafayette, IN) in three joint positions. Isometric strength measurements included external and internal rotation with the arm at the side (i.e. 0° of coronal plane abduction) and external rotation at 90° of abduction in the coronal plane for the involved and non-involved sides. The dynamometer was placed distally on the forearm, just proximal to the wrist joint, along the dorsal radius and ulna for measurement of external rotation and on the volar surface for internal rotation. Measurements were taken three times in each position and averaged to calculate the final isometric strength. All strength measurements were normalized by dividing the involved side by the non-involved side and multiplying by 100% to express strength as a percentage of the non-involved side. Previous literature indicates that chronic pain related to the rotator cuff may have central mechanistic changes potentially affecting bilateral motor control and activation (132-134). However, the physical therapist only collected isometric muscle strength if the individual experienced no pain. If the individual experienced pain at any time, the measurements were stopped, and data was not collected. The repeatability for assessing shoulder strength in symptomatic individuals has been shown to be excellent, with intra-observer repeatability of 0.85 (internal rotation) and 0.92 (external rotation) and inter-observer repeatability of 0.85 (internal rotation) and 0.82 (external rotation) using a handheld dynamometer (135).

Study participants completed two patient-reported outcome measures including the American Shoulder and Elbow Surgeons (ASES) Shoulder Rating Scale (136) and the Western Ontario Rotator Cuff (WORC) Index (137). The ASES was considered the primary outcome measure because it is a shoulder specific outcome measure that has demonstrated evidence of reliability, validity, and responsiveness for individuals with rotator cuff tears (138, 139). The WORC has also demonstrated reliability, validity, and responsiveness and was collected as it is a rotator cuff specific outcome measure (138, 140, 141). Possible scores for both the ASES and WORC were from 0-100, where higher scores indicate greater function.

Ultrasound was used to quantify the anterior-posterior (AP) tear size within the supraspinatus tendon. Assessments were performed with a 6-15 MHz linear array transducer (LOGIQE9, General Electric, MA) by a musculoskeletal radiologist. Individuals were seated with the glenohumeral joint in extension, and the involved side hand on the iliac wing to expose the supraspinatus tendon (142, 143). The transducer was positioned transversely to the supraspinatus tendon, and a short-axis image was acquired. Tear size was quantified as the AP distance of the tear measured perpendicular to a line tangent to the posterior edge of the long head of the biceps tendon. For tear size, unpublished data from our laboratory demonstrated a repeatability within 4.0mm across all observers and was improved in observers with greater ultrasound experience. Studies have also shown high sensitivity and reliability for detection and quantification of rotator cuff tears with accuracy on the order of 1.0mm or less (144-148).

Glenohumeral kinematics during scapular plane abduction were measured using a previously described model-based tracking technique with images acquired from a synchronized biplane radiography system at 50 images/second (35). Individuals underwent a computed tomography (CT) (0.471 x 0.471 x 0.625 mm voxels) scan of the involved shoulder. Computed tomography images were segmented using MIMICS 20 (Materiaise, Leuven, Belgium) to create individual-specific bone models of the humerus and scapula. To assess glenohumeral kinematics, individuals were seated with the involved glenohumeral joint at the center of the system and performed scapular plane abduction. Position in the scapular plane was maintained using a laser pointer attached on the ventral surface of the wrist; individuals were asked to keep the laser pointer within an aligned target. Three trials of scapular plane abduction were performed, lasting two seconds per trial. The trial in which maximum glenohumeral elevation was attained was used for all analyses. Biplane radiographs were distortion corrected and the imaging system was calibrated following established procedures (31, 32, 35). Digitally reconstructed radiographs of the bone models were created from the known geometry of the biplane radiography system. The bone models were then manipulated to match the digitally reconstructed radiographs to the corresponding bones in the biplane radiographic images in all 6 degrees of freedom for each pair of synchronized images throughout the movement using a validated tracking technique (35).

The local coordinate system for each humerus was constructed based on the International Society of Biomechanics recommendations with the origin located at the center of the humeral head (149). However, the scapula coordinate system was modified to create a glenoid based system to describe humeral motion with respect to the center of the glenoid (31). Briefly, the origin was determined as the midpoint between the most anterior and posterior points on the glenoid rim. Local coordinate systems axes were aligned with the most AP and superior-inferior (SI) points on the glenoid rim (150), with the superior and anterior directions considered positive for all individuals. A Y-X-Y Euler angle rotation sequence was used to quantify translations and rotations with accuracy of ± 0.4mm and ± 0.5° for dynamic motion (35). For each data frame, a 3D distance map was calculated between the humeral head and glenoid surfaces. The centroid of the 3D distance map was then quantified as the weighted average of the closest 200mm^2 region between the humeral head and glenoid surfaces, and acts as an estimate of the contact center location during scapular plane abduction (151).

Kinematic variables of interest included maximum AP and SI glenohumeral translations and the contact center location (150) during scapular plane abduction. Due to differences in glenoid geometry between individuals, glenohumeral translations and contact center data were normalized to glenoid AP width and SI height (150). Utilizing the normalized glenohumeral contact data, a contact path length was calculated as the change in frame-by-frame position of the contact center providing a quantification of the distance the humeral head articulated on the glenoid surface during scapular plane abduction. Since the contact path length incorporates articulation in both the AP and SI directions, normalization based upon glenoid AP width and SI height results in a contact path length normalized to glenoid size. A larger contact path length may indicate less joint stability due to less control of the humeral head on the glenoid surface. For each individual, glenohumeral kinematics (i.e. maximum anterior and superior glenohumeral translations) and contact path length were calculated over the final 30° of glenohumeral abduction. Due to variations in the individuals' glenohumeral abduction range of motion during data collection, 30° was chosen to evaluate the largest possible range while minimizing data loss and allowing individual to individual comparisons.

Descriptive statistics were calculated for all variables. Continuous variables were reported as mean and standard deviations (mean ± standard deviation), and categorical variables were reported as frequencies and percentages (%). An a priori power analysis was performed and indicated that 100 individuals was sufficient to detect an absolute difference of 0.3 between the null hypothesis correlation of 0.0 and alternative hypothesis correlation of 0.3 with a power of

80% (alpha=0.05). Normality testing concluded that at least one variable in each proposed relationship testing was non-parametric. Thus, Spearman's correlations were used to determine the relationships between measures of passive glenohumeral ROM, rotator cuff muscle strength, tear size, PROs and glenohumeral kinematics. Due to the exploratory nature of the study and mechanistic hypotheses proposed, a correction for multiple comparisons was not implemented. Thus, significance was set to $P < 0.05$ for all analyses.

3.1.3 Results

Complete data were collected for 86.1**%** of individuals. Individual's age ranged from 40.1-80.6 years and 49.5% of the cohort were males. The most frequently reported duration of shoulder pain prior to entering the study was 3-6 months (33.7%) followed by 1-3 months (26.7%), ≥ 6 months (25.7%) and ≤ 1 month (13.9%) (Table 3.1).

Table 3.1: Demographic characteristics for individuals with symptomatic isolated supraspinatus tears prior to initiation of an exercise therapy program (frequency, %).

Age (years, mean ± SD)	60.6 ± 9.7
Race	
White	83.17% (n=84)
Black or African American	12.87% (n=13)
American Indian or Native	0.99% (n=1)
Asian	0.99% (n=1)
Other	1.98% (n=2)
Ethnicity	
Hispanic or Latino	2.97% (n=3)
Type of work	
Mostly sedentary	42.57% (n=43)
Sedentary, substantial walking	10.89% (n=11)
Moderately active, some lifting	40.60% (n=41)
Demanding	5.94% (n=6)
BMI (mean ± SD)	28.8 ± 4.9
Duration of shoulder pain	
≤ 1 month	13.86% (n=14)
1 – 3 months	26.73% (n=27)
3 – 6 months	33.67% (n=34)
≥ 6 months	25.74% (n=26)
Pain Development	
No injury, gradual onset	57.43% (n=58)
Injury	42.57% (n=43)
Activities of Daily Living	8.91% (n=9)
Motor Vehicle Accident	3.96% (n=4)
Sports	12.87% (n=13)
Other	16.83% (n=17)
Smoker	
Current	7.92% (n=8)
Past	25.74% (n=26)

The range of passive glenohumeral internal rotation, abduction, and flexion in the involved shoulder were 50.3 ± 14.8°, 113.2 ± 20.7°, and 115.2 ± 15.6° respectively. Strength limitations were observed in the involved side for all three joint positions. The largest strength limitation was observed in external rotation at 90° where the involved side strength was 72.1 ± 32.3% of the non-involved side. Passive glenohumeral ROM for the involved side and isometric muscle strengths as a percentage of the non-involved side can be found in Table 3.2. The average ASES and WORC scores were 62.6 ± 17.8 (range 17.5 - 95.0) and 59.0 ± 21.0 (range 4.8 - 97.9), respectively. Tear size was measured in 93.1% of individuals. Reasons for missing data include poor image acquisition and failure of individuals to report at the time of assessment. Supraspinatus tear size ranged from 0.5 – 28.3mm and 65.3% of individuals had a full-thickness tear.

Table 3.2: Kinematic and clinical parameters for individuals with a symptomatic isolated supraspinatus tear prior to initiation of an exercise therapy program (Inv., Involved; Non-Inv., Noninvolved; * indicates data were non-normally distributed).

Glenohumeral Kinematics			
Glenohumeral abduction range analyzed (°)	57.8 ± 13.2 to 87.8 ± 13.2		
Max. Anterior Translation (% glenoid width)*	3.0 ± 3.8		
Max. Superior Translation (% glenoid height)*	3.5 ± 3.8		
Contact Path Length (% glenoid size)*	38.2 ± 20.7		
Isometric Strength	Inv. (N)	Non-Inv. (N)	Normalized (%)
External Rotation 0°*	79.3 ± 40.8	103.9 ± 41.0	77.1 ± 30.3
Internal Rotation 0°	110.8 ± 50.6	132.2 ± 54.5	85.1 ± 23.4
External Rotation 90°	76.1 ± 40.6	108.3 ± 45.0	72.1 ± 32.3
PROM (involved side, °)			
Glenohumeral Abduction*	113.2 ± 20.7		
Glenohumeral Internal Rotation 90°	50.3 ± 14.8		
Glenohumeral Flexion*	115.2 ± 15.6		
Patient Reported Outcomes (Total Score)			
ASES*	62.6 ± 17.8		
WORC	59.0 ± 21.0		

Sixteen individuals did not have ≥30° of available in-vivo glenohumeral abduction and were excluded from all kinematic analyses. The range of glenohumeral abduction analyzed for all kinematic outcome measures was from 57.8 ± 13.2° to 87.8 ± 13.2°. Average glenoid width and height used to normalize glenohumeral translations and contact path length were 26.7 ± 3.6mm and 34.2 ± 3.7mm**,** respectively. Furthermore, 84.7% of individuals had maximum anterior translations less than or equal to 6.0% glenoid width (ranged from 0% - 15.6% glenoid width) and 91.8% of individuals had maximum superior translations less than or equal to 9.0% glenoid height (ranged from 0.0% to 17.6% glenoid height). Approximately 65.9% percent of individuals had contact path lengths less than 40.7% glenoid size and 20.0% of individuals had contact path lengths between 40.7% - 56.7% glenoid size.

The associations between isometric strength with contact path length and maximum superior glenohumeral translations were all non-significant (Table 3.3). Specifically, there were no significant associations between external rotation strength measured with the arm at 0° and external and internal rotation strength with the arm at 90° of abduction with contact path length and maximum superior glenohumeral translation (ρ^2 ranged from 0.00-0.03, P > 0.12).

Table 3.3: Correlation matrix summarizing relationships between isometric rotator cuff muscle strength and glenohumeral kinematics/arthrokinemtics in individuals with a symptomatic isolated supraspinatus tear prior to initiation of an exercise therapy program.

	Contact Path Length			**Maximum Superior Translation**		
	ρ	**ρ ^2**	**P**	**ρ**	**ρ ^2**	**P**
ER0° Strength	0.04	0.00	0.74	-0.01	0.00	0.96
IR0° Strength	-0.03	0.00	0.81	-0.17	0.03	0.12
ER90° Strength	-0.05	0.00	0.68	0.11	0.01	0.34

There were no significant associations between supraspinatus tear size and contact path length or with isometric external or internal rotation strength at 0° of abduction and external rotation at 90° of abduction. (P > 0.46, Table 3.4). No relationships were observed between passive ROM measurements and maximum superior and anterior glenohumeral translations (P > 0.27, Table 3.5).

Table 3.4: Correlation matrix summarizing relationships between anterior-posterior tear size, contact path length and isometric rotator cuff muscle strength in individuals with a symptomatic isolated supraspinatus tear prior to initiation of an exercise therapy program (IR, Internal Rotation; ER, External Rotation).

	Contact Path Length			IR0° Strength			ER0° Strength			ER90° Strength		
	ρ	ρ^2	P	ρ	ρ^2	P	ρ	ρ^2	P	ρ	ρ^2	P
AP Tear Size	-0.05	0.00	0.65	-0.04	0.00	0.71	-0.08	0.01	0.46	-0.07	0.00	0.53

Table 3.5: Correlation matrix summarizing relationships between passive range of motion and maximum glenohumeral translations in individuals with a symptomatic isolated supraspinatus tear prior to initiation of an exercise therapy program (IR, Internal Rotation; PROM, Passive Range of Motion; GH, Glenohumeral; ABD, Abduction).

	Maximum Superior Translation			Maximum Anterior Translation		
	ρ	ρ^2	P	ρ	ρ^2	P
IR90° PROM	-0.12	0.01	0.27	0.08	0.01	0.45
GH ABD PROM	0.07	0.01	0.52	-0.12	0.01	0.30
GH Flexion PROM	-0.09	0.01	0.44	-0.04	0.00	0.74

There were no significant associations between ASES scores and WORC scores with maximum superior and anterior glenohumeral translations ($P > 0.18$, Table 3.6). Furthermore, there was no significant association between contact path lengths and ASES scores, but there was a significant positive association between contact path lengths and WORC scores ($\rho = 0.25$, $P = 0.03$, Table 3.6). Thus, as contact path lengths increased, WORC scores increased.

Table 3.6: Correlation matrix summarizing relationships between glenohumeral kinematics and arthrokinematics and patient reported outcomes in individuals with a symptomatic isolated supraspinatus tear prior to initiation of an exercise therapy program (ASES, American Shoulder and Elbow Surgeons; WORC, Western Ontario Rotator Cuff Index; * indicates significance at P<0.05).

	ASES Score			WORC Score		
	ρ	**ρ^2**	**P**	**ρ**	**ρ^2**	**P**
Maximum Superior Translation	-0.06	0.00	0.63	0.15	0.02	0.18
Maximum Anterior Translation	0.15	0.02	0.18	0.07	0.00	0.55
Contact Path Length	0.17	0.03	0.13	0.25	0.06	0.03*

3.1.4 Discussion

The present study described the presentation of individuals with an isolated supraspinatus tendon tear. Overall, the individuals in this study presented with limitations in isometric muscle strength (compared to non-involved side), minimal restrictions in passive glenohumeral ROM relative to the normal expected range of glenohumeral abduction, flexion, and internal rotation (131) reported in the literature and assuming 2:1 scapulohumeral rhythm, and pain and disability as measured by the ASES and WORC. Furthermore, there were no associations observed between passive glenohumeral ROM, isometric rotator cuff muscle strength, supraspinatus tear size, and glenohumeral kinematics during scapular plane abduction. Additionally, there were no associations observed between glenohumeral kinematics during scapular plane abduction and PROs, with the exception of contact path lengths and WORC scores.

The implications of the findings regarding the initial presentation of individuals with a symptomatic isolated supraspinatus tear are for the development of an exercise therapy program focusing on individualized treatment. Specific exercises utilized should be based on the impairments identified during the initial examination, and a set of pre-defined clinical decision-making criteria should be utilized to address each impairment and guide progression through the program. For example, the therapist may choose to implement ROM or stretching exercises or joint mobilization when a loss of ROM is present compared to the non-involved side. Exercises will then be performed at a set dosage until ROM is within normal limits or equal to the non-involved side. A similar decision-making process would also be utilized for impairments in muscle strength, where isometric, isotonic, and progressive resistive exercises may be implemented to address the observed weaknesses.

Interestingly, all of the hypothesized mechanistic relationships proposed in the present study were not supported by the results. Individuals with greater internal and external rotation strength did not demonstrate less superior migration and more joint stability. These findings may indicate that various magnitudes of strength of the subscapularis, infraspinatus, and teres minor can maintain joint stability given the tear was isolated to the supraspinatus tendon. Numerous studies have described the ability of the transverse force couple to maintain glenohumeral joint stability through the medially and inferiorly directed forces in the presence of isolated supraspinatus tears (9, 20, 28). Thus, although it was hypothesized that greater strength of the muscles comprising the transverse force couple would decrease superior glenohumeral translations and increase joint stability, the finding does remain consistent with previous literature regarding the transverse force couple. For comparison, the contact path length has been shown to be 31.6 ± 11.0 % glenoid height (range 17.2 to 58.8) during coronal plane abduction in aged-matched controls between the range of 20° to 70° of glenohumeral elevation. Thus, individuals in the current cohort with isolated supraspinatus tendon tears experienced larger contact path lengths compared to previously reported controls (33).

The findings that AP tear size was not associated with internal and external rotation strength or contact path length has two implications. First, given a tear isolated to the supraspinatus tendon, functional strength of the subscapularis, infraspinatus, and teres minor were not affected by the magnitude of the tear size. Second, given a tear isolated to the supraspinatus tendon, larger tears do not result in less glenohumeral joint stability. Two previous studies using cadavers that demonstrated no significant alterations in glenohumeral translations with 1, 3, or 5cm supraspinatus tears (given the infraspinatus tendon is intact)(28), as well as no significant changes in glenohumeral joint reaction force magnitudes during active scapular plane abduction in isolated incomplete or complete tears of the supraspinatus tendon (20). In combination, these two findings indicate that individuals with rotator cuff tears isolated to the supraspinatus tendon do not exhibit restrictions in strength or less joint stability based upon the size of the isolated supraspinatus tear.

Greater ranges of passive glenohumeral internal rotation, abduction, and flexion were not related to maximum anterior and superior glenohumeral translations during scapular plane abduction *in-vivo*. This suggests that varying amounts of available passive glenohumeral ROM in the presence of a rotator cuff tear isolated to the supraspinatus tendon does not affect maximum glenohumeral translations during scapular plane abduction. Given the tear is isolated to the supraspinatus tendon and no capsular restrictions are present as indicated by more than 30° of internal and external rotation range of motion, normal function of the glenohumeral joint is possible. These results differ from previous studies in cadavers that demonstrated increased anterior and superior glenohumeral translations following posterior capsular plication to limit range of motion (121). The results of this study likely differ from cadaveric models mimicking posterior-inferior capsular tightness due to their inability to account for activation of the rotator cuff muscles, as well as the exclusion of individuals with less than 30° of internal and external rotation range of motion.

The hypothesized relationships between maximum anterior and superior glenohumeral translations and PROs were also not supported. This suggests that PROs were not influenced by glenohumeral translations in individuals with isolated supraspinatus tears (coronal and transverse plane couples intact) and more than 30° of internal and external rotation range of motion. Previous studies assessing in-vivo glenohumeral translations in healthy control subjects have reported average superior-inferior translations between 0.04 ± 1.3mm and -0.02 ± 1.4mm and anterior translations between 1.2 ± 2.0mm and 0.4 ± 2.0mm from 90° to 120° of humerothoracic abduction

(152). Assuming 2:1 scapulohumeral rhythm, humerothoracic abduction in this study ranged between 86.7 ± 19.8° and 131.7 ± 19.8° with maximum superior translations of 3.5 ± 3.8% glenoid height (1.2 ± 1.3mm) and maximum anterior translations of 3.0 ± 3.8% glenoid width (0.8 ± 1.0mm). In contrast to the ASES score, the WORC score was found to positively relate to contact path length, which may indicate that the WORC score does not properly reflect glenohumeral joint stability, as it would be expected that higher scores would relate to a more stable joint. However, the observed relationship was weak and the variation in WORC scores explained by contact path lengths was only 6.0% (Table 3.6). Therefore, the observed relationship is likely not clinically significant and may have occurred due to chance given the multiple correlations evaluated in the study. Thus, from a biomechanical perspective, individuals with isolated supraspinatus tears included in this study do not present with clinically significant differences in glenohumeral kinematics that would likely affect PROs.

Regarding PROs, a previous study investigated the effects of a 12-week exercise therapy program on glenohumeral kinematics (during coronal plane abduction), isometric muscle strength, and PROs in five individuals with symptomatic full-thickness supraspinatus tears (31). Average WORC and ASES scores prior to exercise therapy were lower compared to the current study by 16.1 and 11.9 points, respectively. An additional study investigating the effectiveness of physical therapy in treating atraumatic full thickness rotator cuff tears in 452 individuals reported average WORC and ASES that were 11.8 and 8.1 points lower than the current study, respectively. However, only 70% of individuals had tears isolated to the supraspinatus tendon (30). Differences observed in PROs prior to exercise therapy between studies demonstrates the importance of understanding factors relating to PRO scores. Varying PRO scores have been related to active ROM (flexion, abduction, and rotations) and muscle strength in individuals with different shoulder pathologies (153, 154). Furthermore, the effects of exercise therapy and rotator cuff repair agreed with the findings of the current study that glenohumeral kinematics were not related to PROs and subjective self-reported outcomes may be more influenced by pain relief and psychosocial factors such as patient expectation or mental health status (37, 155). Thus, future work should investigate the individual contribution of varying factors on PROs in individuals with isolated supraspinatus tendon tears prior to exercise therapy.

A limitation of this study is the inclusion of partial- and full-thickness tears in all analyses. In future studies, partial- versus full-thickness tears will be investigated as separate groups to determine the effects of tear thickness on glenohumeral kinematics and PROs as it has been shown that full-thickness tears are associated with worse PROs (156). Additional limitations of the study were inclusion of a single movement to assess in-vivo glenohumeral kinematics and analyses only being performed over the end range of motion. However, due to the primary role of the supraspinatus for glenohumeral abduction and clinical importance of the end range of motion, assessing glenohumeral kinematics in this manner was most reasonable. To better understand the effects of isolated supraspinatus tears, more provocative movements should be investigated. Future work will investigate glenohumeral kinematics during additional movements, as well as determining the biomechanical and clinical factors that predict the success or failure of a 12-week structured exercise therapy program.

3.1.5 Conclusions

The present study demonstrates that individuals with isolated supraspinatus tears present with minor limitations in shoulder motion and rotator cuff muscle strength. Furthermore, these limitations were not associated with altered glenohumeral kinematics or PROs prior to an exercise therapy program. Thus, from a biomechanical perspective, individuals with isolated supraspinatus tears (coronal and transverse plane force couples intact) and no capsular restrictions as indicated by more than 30° of internal and external rotation range of motion do not exhibit changes in glenohumeral kinematics.

4.0 Aim 2: Effects of a 12-Week Personalized Exercise Therapy Program

4.1 Individualized Exercise Therapy Improves Shoulder Function and Patient Reported Outcomes Without Increasing Tear Size for Individuals with Isolated Supraspinatus Tear

4.1.1 Introduction

Although initial treatment for symptomatic rotator cuff tears remains controversial, non-operative treatment is generally prescribed and is successful in approximately 50-75% of individuals (30, 109-113). Exercise therapy has been shown to have beneficial effects on range of motion (ROM), muscle strength, and patient reported outcomes (PROs) (30-33). However, few studies sufficiently describe the exercise therapy protocol, making it difficult to assess the effects of exercise on glenohumeral kinematics (119), and tear size has not been quantified immediately before and after exercise therapy. Understanding changes in glenohumeral kinematics and tear propagation following an individualized exercise therapy program may provide further insight on these factors' role in the success of exercise therapy.

Regarding changes in glenohumeral kinematics/arthrokinematics following exercise therapy, previous studies observed conflicting results with reports of reduction in contact path length (CPL) of 29% (31), or no changes in CPL but significant increases in the superior-inferior contact center range (range of movement of humeral head on glenoid surface in superior-inferior direction) (33). Given the CPL quantifies the amount of movement of the humeral head on the glenoid, a smaller CPL may be indicative of a more stable glenohumeral joint. Another study found no changes in glenohumeral kinematics following exercise therapy during an internal-external rotation movement (32). The inconsistency for exercise therapy to address glenohumeral kinematics may be a potential reason for unsuccessful outcomes following exercise therapy, emphasizing the need to define a more individualized program (32).

Controversy surrounding the likelihood of rotator cuff tear propagation following non-operative treatment exists. Some argue that operative treatment prevents tear propagation compared to exercise therapy (26, 27). Tear propagation is hypothesized to occur due to muscle imbalances caused by the existing tear resulting in overloading of neighboring rotator cuff tendons (28). Strengthening exercises during non-operative treatment may help restore balance to the intact rotator cuff musculature and reduce the force applied to the torn and surrounding intact rotator cuff. However, rotator cuff tear size has not been determined immediately before and after exercise therapy.

The objective of the study was to evaluate changes in joint function, patient reported outcomes and tear size following an individualized approach for non-operative exercise therapy for treatment of individuals with a symptomatic isolated supraspinatus tendon tear. Variables of interest included in-vivo glenohumeral kinematics and arthrokinematics, passive glenohumeral ROM, isometric rotator cuff muscle strength, PROs, and rotator cuff tear size. It was hypothesized that exercise therapy for treatment of an isolated supraspinatus tear will result in: 1) Increased passive glenohumeral ROM, isometric rotator cuff muscle strength and PROs, 2) no increases in rotator cuff tear size, and 3) improved glenohumeral kinematics and arthrokinematics.

4.1.2 Methods

4.1.2.1 Subjects

One hundred nine individuals (mean age 60.9 ± 9.9 years, mean Body Mass Index (BMI) 28.7 ± 5.0 kg/m^2) were recruited to participate in this prospective longitudinal observational study and provided IRB-approved written informed consent prior to performance of any research procedure. Individuals with a symptomatic partial- (>50%) or full-thickness rotator cuff tear isolated to the supraspinatus tendon were included in the study if they were 40 years of age or older with BMI <40 kg/m^2 and had at least 110° range of humerothoracic elevation (ensuring the individual could participate in biplane radiography testing to prevent unnecessary radiation exposure). Individuals were excluded if they had a work-related injury, an asymptomatic rotator cuff tear, severe capsular tightness as evidenced by less than 30° of internal or external rotation, or diabetes mellitus.

4.1.2.2 Overall Research Procedures

The current study included a testing session before and after a 12-week individualized exercise therapy program to determine the immediate changes following an exercise therapy program for individuals with isolated supraspinatus tears. Individuals underwent a 12-week exercise therapy program and study variables described below were quantified before and immediately after exercise therapy.

4.1.2.3 Description of Exercise Therapy Program

Individuals underwent a 12-week exercise therapy program (12-visits in total) for treatment of a rotator cuff tear at the University of Pittsburgh Physical Therapy Clinical and Translational Research Center. The program utilized specific individualized criteria related to the study participant's pain, ROM and strength to tailor the interventions to each individual's unique clinical presentation (157). The overarching framework focused on restoring passive glenohumeral ROM and strengthening of the rotator cuff and scapular muscles. However, depending on the initial staging of the individual based on tissue irritability, the identified impairments, and response to treatment, the selection and progression of interventions were individualized (158). Overall, prior to exercise therapy participants in the cohort demonstrated decreased ROM, external rotation weakness, and pain/disability as measured by the ASES and WORC (21).

Range of motion and stretching exercises, as well as joint mobilization were performed as necessary to restore normal passive glenohumeral ROM. As ROM was restored, achievement of clinical criteria determined when interventions that focused on increasing strength of the rotator cuff and scapular muscles and task specific activities were initiated. Three levels of clinical decision-making led to the selection of individual specific interventions during each visit. The first level dealt with determining the stage at which the individual presented. Information regarding the pain-restriction sequence assisted the clinician in placing the individual in either the low irritability, intermediate irritability or highly irritable stage (Table 4.1).

Table 4.1: Criteria utilized to determine an individuals pre-exercise therapy irritability status.

Category	**Irritability Classification**		
	Low	**Intermediate**	**High**
Pain	≤3/10 -No pain at rest -No/low pain with ADLs	4-6/10 -Moderate to low pain -Intermittent pain at rest -Low to moderate pain with ADLs	≥7/10 -Pain at rest and at night
Range of Motion (ROM)	Minimal pain with overpressure	Pain at end of ROM	Limited compared to contralateral in active and passive ROM and pain before end of ROM
Strength	No pain with resisted exercises	Weakness on resisted testing	Pain and weakness with resisted testing
Disability	Low level	Moderate level	High level

Second level decision making related to determining if passive and/or active ROM was restricted. Restricted ROM led the clinician to determine the cause as either limited accessory motion or loss of tissue extensibility and appropriate interventions were delivered (See Figure 4.1 and Figure 4.2). The final level of assessment made was the presence of weakness to determine the appropriate resistance and functional exercises. Exercise resistance and number of repetitions were determined based on a modification of the daily adjustable progressive resistance exercise program (159).

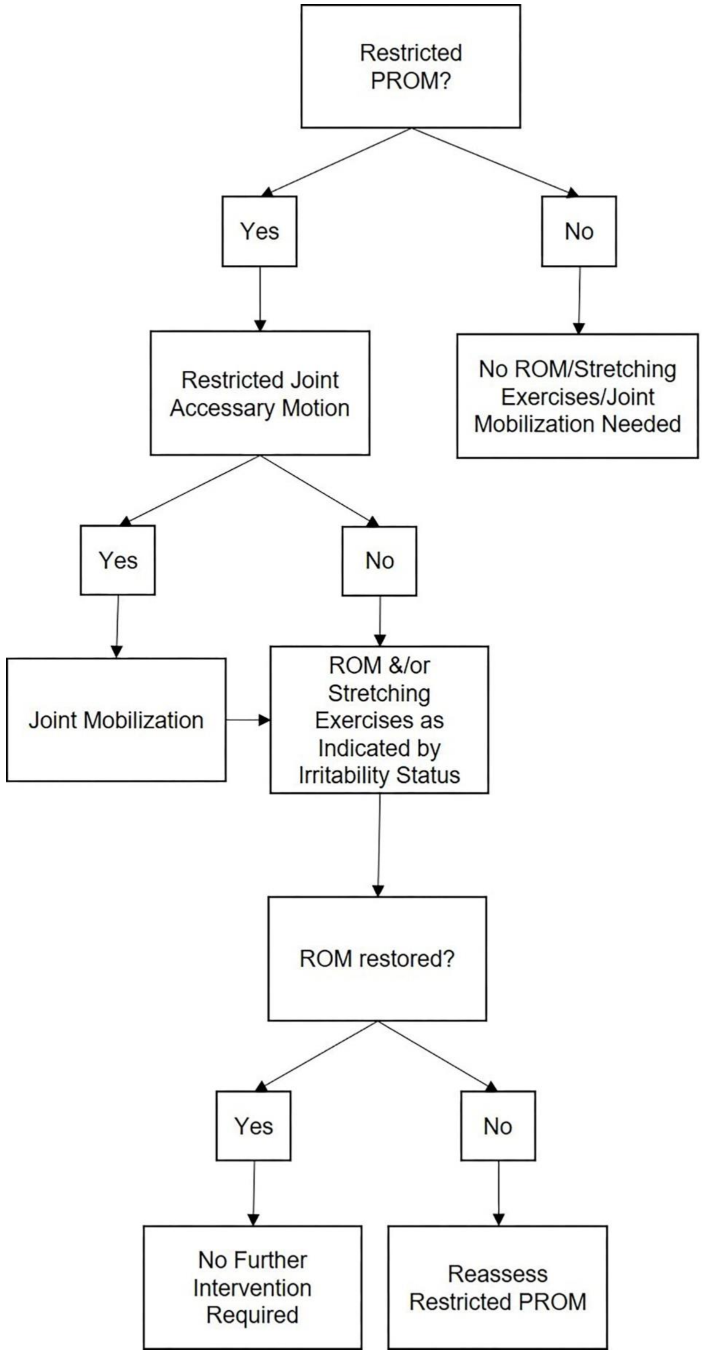

Figure 4.1: Flowchart of the exercise therapy protocol and clinical decision making for passive range of motion (PROM) utilized to determine individuals' progression throughout the 12-week individualized program.

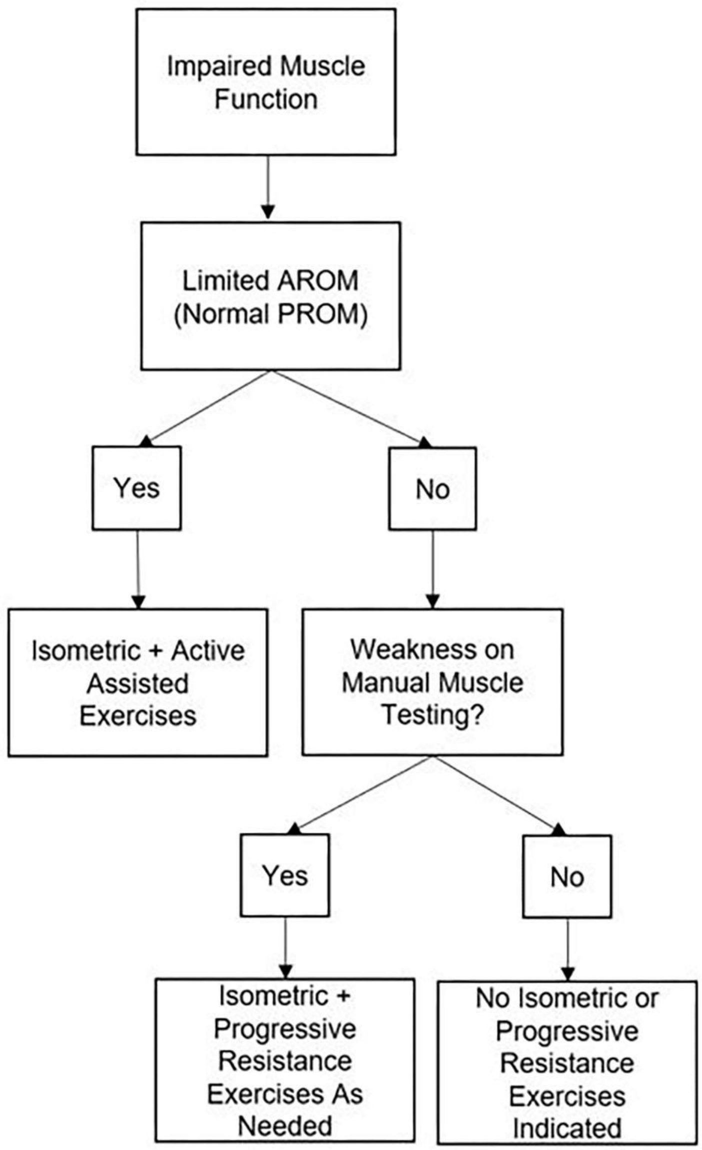

Figure 4.2: Flowchart of the exercise therapy protocol and clinical decision making for impaired muscle function/active range of motion (AROM) utilized to determine individuals' progression throughout the 12-week individualized program.

4.1.2.4 Measurement of Range of Motion and Rotator Cuff Strength

Passive glenohumeral ROM and isometric strength of the rotator cuff muscles were measured by one of three certified physical therapists. Passive glenohumeral abduction, flexion, internal and external rotation at 90° of humerothoracic abduction were assessed using a goniometer on the involved side. All measurements were made in the supine position. These passive ROM measurements were chosen as they assess capsular tightness and glenohumeral joint function. Previous literature assessing isolated glenohumeral ROM in healthy individuals demonstrated intra- and inter-observer repeatability ranging from 0.62 to 0.84 and 0.62 to 0.86, respectively, for various joint positions (131).

Isometric strength measurements of the rotator cuff were taken as previously described (31, 32) using a handheld dynamometer (Lafayette Manual Muscle Testing System, Lafayette Instrument Company, Lafayette, IN) in four joint positions. Isometric strength measurements included external and internal rotation with the arm at the side, external rotation at 90° of abduction in the coronal plane, and scapular plane abduction at 90° of humerothoracic abduction. Measurements were taken three times in each position and averaged to calculate isometric strength. All strength measurements were normalized as a percentage compared to the noninvolved shoulder. The repeatability for assessing shoulder strength in symptomatic individuals has been shown to be excellent, with intra-observer repeatability of 0.85 (internal rotation) and 0.92 (external rotation) and inter-observer repeatability of 0.85 (internal rotation) and 0.82 (external rotation) using a handheld dynamometer (135).

4.1.2.5 Patient Reported Outcomes

Participants completed the American Shoulder and Elbow Surgeons (ASES) Shoulder Rating Scale (136) and the Western Ontario Rotator Cuff (WORC) Index (137). The ASES and WORC have demonstrated evidence of reliability, validity, and responsiveness for individuals with rotator cuff tears (138, 139) (138, 140, 141). Possible scores for both were from 0-100, where higher scores indicated greater function and less pain.

4.1.2.6 Ultrasound Measurement of Rotator Cuff Tear Size

Ultrasound was used to quantify the anterior-posterior (AP) tear size within the supraspinatus tendon. Assessments were performed with a 6-15 MHz linear array transducer (LOGIQE9, General Electric, MA) by a musculoskeletal radiologist. Individuals were seated with the glenohumeral joint in extension, and the involved side hand on the iliac wing to expose the supraspinatus tendon (142, 143). Tear size was quantified as the AP distance of the tear measured perpendicular to a line tangent to the posterior edge of the long head of the biceps tendon. Diagnostic ultrasound has high sensitivity and reliability for detection and quantification of rotator cuff tears with accuracy on the order of 1.0mm or less (144-148). Changes in tear size of 5.0mm or more is considered clinically meaningful and detectable based on previous literature (160). Additionally, internal unpublished data demonstrated a minimal detectable change of 4.6mm, an intra-observer repeatability of 0.51-0.87 (increased with experience) and an inter-observer repeatability of 0.32 for measuring tear size in individuals with symptomatic isolated supraspinatus tears. Thus, based on the clinically meaningful threshold and minimal detectable change, any absolute change in tear size greater than 5.0mm was considered a true change beyond measurement error.

4.1.2.7 Measurement of Glenohumeral Kinematics

Glenohumeral kinematics during scapular plane abduction were measured using a synchronized biplane radiography system at 50 images/second. Individuals underwent a computed tomography (0.464 x 0.464 x 0.625 mm voxels) scan of the involved shoulder and images were segmented using MIMICS 20 (Materialise, Leuven, Belgium) to create individual-specific humerus and scapula bone models. To assess glenohumeral kinematics, individuals were seated with the involved glenohumeral joint centered in the system and performed scapular plane abduction. All individuals completed the movement with a straight arm (elbow extended) and a metronome was used to help the subject maintain a steady abduction speed. Arm position in the desired plane was maintained using a laser pointer strapped to the involved side hand, with individuals asked to keep the laser dot within a properly aligned stripe of tape on a target surface. Three trials of scapular plane abduction were performed before and after exercise therapy. The trial in which maximum glenohumeral elevation was attained on each test day was used for all analyses.

Biplane radiographs were distortion corrected and the imaging system was calibrated following established procedures (31, 32, 35). Digitally reconstructed radiographs of the bone models were created from the CT-based individual specific bone models and the known geometry of the biplane radiography system. A semi-automated matching process was used to optimize the correlation between the digitally reconstructed radiographs and the distortion-corrected radiographs for each pair of synchronized images throughout the movement (35).

The local coordinate system for each humerus was constructed based on the International Society of Biomechanics recommendations, with the origin located at the center of the humeral head (149). The scapula coordinate system was modified to create a glenoid based system to describe humeral motion with respect to the center of the glenoid (31). Local coordinate systems axes were aligned with the most AP and superior-inferior (SI) points on the glenoid rim (150), with the superior and anterior directions considered positive. A Y-X-Y Euler angle rotation sequence was used to quantify translations and rotations with accuracy of ± 0.4mm and ± 0.5°, respectively (35). For each data frame, a 3D distance map was calculated between the humeral head and glenoid surfaces. The centroid of the 3D distance map was then quantified as the weighted average of the closest 200mm^2 region between the humeral head and glenoid surfaces, and acts as an estimate of the contact center location (151).

Kinematic variables of interest included maximum glenohumeral elevation, maximum AP and SI glenohumeral translations and the contact center location (150). Glenohumeral translations and contact center data were normalized to glenoid AP width and SI height (150). The CPL was calculated as the change in frame-by-frame position of the contact center providing an estimate of the distance the humeral head articulated on the glenoid surface. Normalization based upon glenoid AP width and SI height results in a CPL normalized to glenoid size. A larger CPL may indicate less joint stability due to less control of the humeral head on the glenoid surface. Due to variations in ROM between individuals, comparisons were made on an individual basis using the largest shared ROM between data collection sessions.

4.1.2.8 Statistical Analysis

Continuous variables were reported as mean and standard deviations or median and interquartile range depending on normality and categorical variables were reported as frequencies and percentages. Failure of the exercise therapy program was defined as an individual opting for operative treatment or injection prior to the conclusion of the 12-week program. To determine changes in variables, paired t-tests and Wilcoxon Signed Rank tests were utilized for normally and non-normally distributed data, respectively. An individual's data were only used for comparisons if pre- and post-exercise therapy data were available. Significance was set to $P < 0.05$ for all analyses.

4.1.3 Results

Overall, 92.7% of individuals successfully completed the 12-week structured exercise therapy program. Furthermore, 38 individuals began the program in the low irritability stage, 55 in the intermediate irritability stage and 14 in the highly irritable stage (missing data for 2 individuals). Three individuals failed to complete the 12-week program (2 surgery, 1 injection) and five individuals were either lost to follow-up or withdrew from the study. The number of individuals with complete pre- and post-exercise therapy data for each variable is shown in Table 4.2. Reasons for missing data included lost to follow-up, withdrawal, inability to report for follow-up due to COVID-19 restrictions, or failure to report for a scheduled study visit.

Table 4.2: Number of Individuals with Complete Pre- and Post-Exercise Therapy Data for Each Variable

Measure	Frequency (%)
PROM	93 (85.3%)
Isometric Strength	90 (82.6%)
ASES	71 (65.1%)
WORC	97 (89.0%)
Glenohumeral Kinematics	90 (82.6%)
Tear Size	81 (74.3%)

Improvements in passive glenohumeral ROM (P=0.001 to 0.012), isometric muscle strength (P=0.001), and PROs (P=0.001) occurred following the 12-week individualized exercise therapy program (Table 4.3). Measures of passive glenohumeral ROM increased by 5.5-10.0% relative to pre-exercise therapy depending on the motion. Isometric muscle strength increased by 9.3-18.9% relative to pre-exercise therapy depending on the muscle group being tested. The ASES and WORC scores also increased by 26.3% and 35.7%, respectively. Overall, 59.2% (MCID=12.0) and 68.0% (MCID=13.5) of individuals experienced clinically meaningful increases in the ASES and WORC, respectively (161, 162).

Table 4.3: Kinematics, Arthrokinematics, and Clinical Parameters for Individuals with a Symptomatic Isolated Supraspinatus Tear Pre- and Post-Exercise Therapy

Measure	Pre	Post	P
Glenohumeral Kinematics			
Max. Glenohumeral Elevation (°)	83.5 ± 17.8	88.0 ± 13.2	0.001*
Max. Anterior Translation (% glenoid width)[a]	1.9 (0.0-5.7)	1.4 (0.0-5.3)	0.285
Max. Superior Translation (% glenoid height)[a]	2.0 (0.0-6.7)	2.4 (0.3-7.1)	0.266
Contact Path Length (% glenoid size)[a]	42.4 (31.3-55.5)	35.9 (25.3-55.2)	0.001*
Isometric Strength (involved/uninvolved, %)			
ER0°[a]	74.3 (59.3-95.8)	85.1 (74.6-96.8)	0.001*
IR0°	84.4 ± 24.2	94.8 ± 17.4	0.001*
ER90°[a]	67.2 (53.2-88.1)	88.9 (70.9-99.6)	0.001*
Scapular Plane Abduction[a]	79.4 (58.6-93.1)	90.3 (79.5-101.7)	0.001*
PROM (involved side, °)			
Glenohumeral Abduction[a]	113.0 (104.8-123.3)	120.0 (114.0-131.0)	0.001*
Glenohumeral IR90	50.7 ± 14.5	55.7 ± 13.7	0.001*
Glenohumeral Flexion[a]	115.0 (107.0-121.0)	120.0 (113.0-129.0)	0.001*
Glenohumeral ER90[a]	83.0 (72.0-93.0)	86.0 (78.0-93.0)	0.012*
Patient Reported Outcomes (Total Score)			
ASES[a]	70.0 (58.3-80.8)	89.5 (81.7-94.2)	0.001*
WORC[a]	60.5 (47.2-77.7)	89.0 (76.7-95.9)	0.001*
Tear Size (mm)			
Anterior-Posterior Tear Size[a]	10.9 (7.8-14.9)	10.5 (7.2-14.9)	0.313

ER, external rotation; IR, internal rotation; ASES, American Shoulder and Elbow Surgeons; WORC, Western Ontario Rotator Cuff Index.

* Significant at $p<0.05$

[a] Data were non-normally distributed for at least one timepoint, Median (Interquartile Range)

Normally Distributed, (Mean ± SD)

No overall changes in AP tear size occurred following the 12-week individualized exercise therapy program (P=0.313, Table 4.3). Specifically, 7.4% of individuals (n=6) experienced a decrease in tear size greater than 5.0mm (-7.5 ± 1.8mm), 6.2% of individuals (n=5) experienced an increase in tear size greater than 5.0mm (7.2 ± 1.5mm), and 86.4% of individuals (n=70) experienced no detectable changes in tear size (Figure 4.3, Figure 4.4).

During kinematic testing, maximum glenohumeral elevation increased by 4.5 ± 12.3° (P=0.001) and CPL decreased by 6.5% glenoid size following exercise therapy (P=0.001, Table 4.3). No changes in maximum anterior or superior glenohumeral translations were observed following exercise therapy (P=0.285 and P=0.266, respectively, Table 4.3).

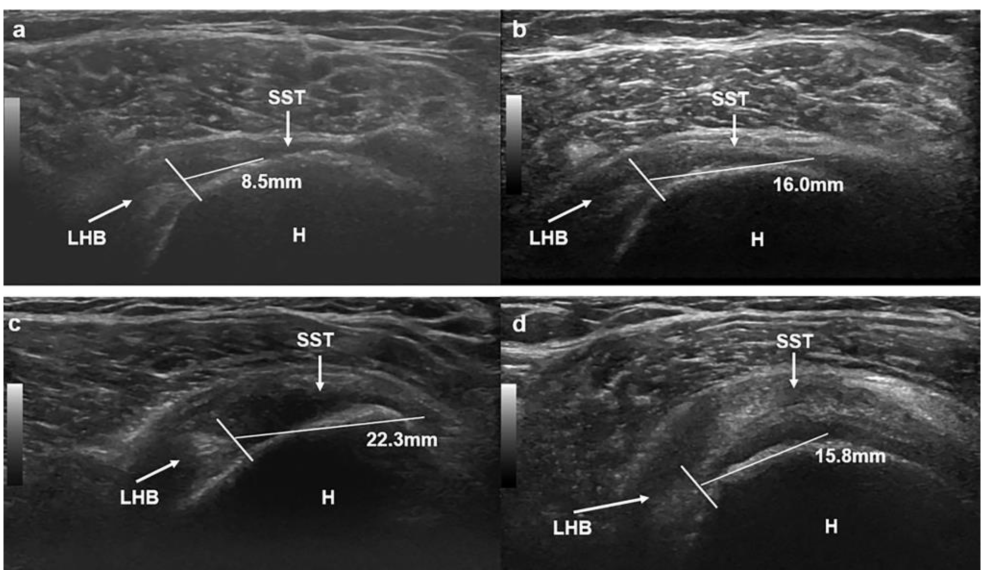

Figure 4.3: Images a and b are the before and after exercise therapy ultrasound findings respectively for an individual whose tear size increased. Images c and d are the before and after exercise therapy ultrasound findings respectively for an individual whose tear size decreased (Humerus, H; Long head of the biceps tendon, LHB; Supraspinatus Tendon, SST).

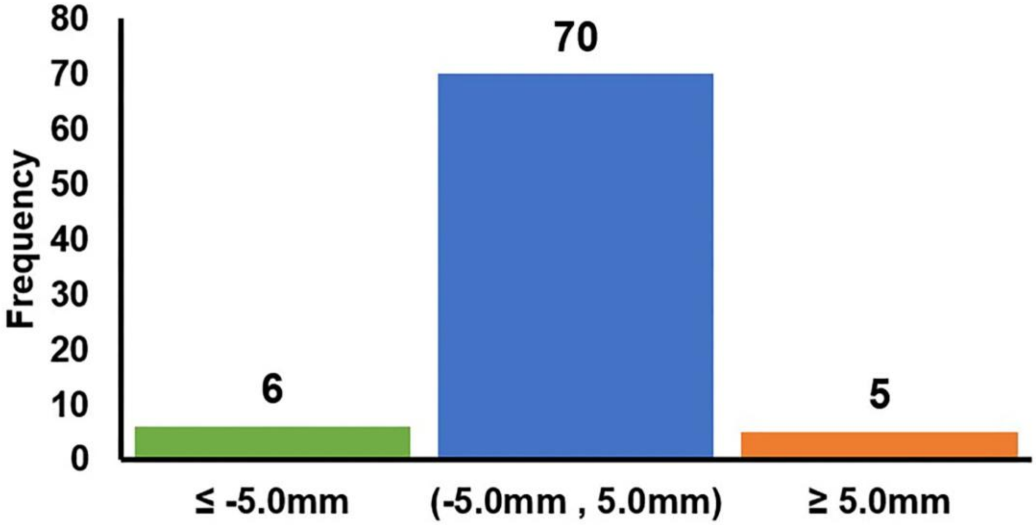

Figure 4.4: Histogram demonstrating the number of individuals whose supraspinatus tear size decreased by 5.0mm or more, had no detectable change, or increased by 5.0mm or more after a 12-week personalized exercise therapy program.

4.1.4 Discussion

The present study determined the immediate changes in joint function, patient reported outcomes and tear size following an individualized exercise therapy program for individuals with a symptomatic isolated supraspinatus tear. The main findings of the study were that a 12-week individualized exercise therapy program led to: 1) Increased passive glenohumeral ROM and isometric muscle strength, 2) clinically important increases in PROs without increases in tear size, and 3) improved in-vivo glenohumeral arthrokinematics and kinematics.

The hypothesis that in-vivo glenohumeral arthrokinematics and kinematics would improve was partially supported. First, CPL decreased which may indicate that the glenohumeral joint was more stable post-exercise therapy. This was likely due to the increased strength of the subscapularis and infraspinatus/teres minor muscles, which has been shown to maintain joint stability through the glenohumeral joint force couples in the presence of an isolated supraspinatus tear (20). Contact path length in healthy controls during coronal plane abduction has been shown to be 31.6 ± 11.0 and 28.0 ± 10.3 % glenoid height, while individuals with asymptomatic rotator cuff tears have significantly increased contact path lengths in comparison indicating less joint stability (33, 41). Individuals in the current study had similar magnitudes of the contact path length following exercise therapy compared to the referenced healthy controls.

Maximum glenohumeral elevation increased by 4.5° post-exercise therapy. Healthy individuals over the age of 45 years have maximum glenohumeral elevation of 98.0 ± 7.0° (43). In the current study, 19.4% of individuals exceeded 98.0° and 41.8% of individuals were within one standard deviation following exercise therapy. No changes in maximum anterior or superior glenohumeral translations occurred post-exercise therapy, which may be due to pre-exercise therapy values being similar to healthy individuals (152, 163, 164).

Individuals in the current study experienced improved passive glenohumeral ROM, isometric muscle strength and clinically meaningful improvements in ASES and WORC scores which is in agreement with previous studies (30-33). In regard to the percentage of individuals who did not achieve the MCID for the ASES and WORC, it is important to consider their pre-exercise therapy scores. Overall, 50.0% of individuals had pre-exercise therapy ASES scores >70.0 and WORC scores >60.5. Additionally, for the WORC, 37.1% of individuals had scores >70.0. Due to the higher pre-exercise therapy scores, the MCID may be more difficult to achieve, potentially indicating MCIDs should be adjusted depending on pre-exercise therapy status.

Overall, no increases in AP tear size of the supraspinatus tendon occurred. According to previous literature, a change in tear size of 5.0mm or more is considered clinically meaningful (160). Only five individuals in the current study experienced clinically meaningful and detectable increases greater than 5.0mm in tear size. The current study provides novel information regarding tear size through quantification of rotator cuff tear size immediately before and after exercise therapy. Some argue that operative treatment is necessary to prevent rotator cuff tear propagation (26, 27), whereas others hypothesized that improved strength in the surrounding and intact rotator cuff may better balance forces crossing the glenohumeral joint and reduce tension on the tear (28). The current study supports the risk of tear progression following an individualized exercise therapy program was minimal given only 6.2% of individuals experienced increased tear size. For individuals that experienced a negative change in tear size, it is hypothesized that scar tissue may have formed as it is unlikely to be spontaneous healing.

Overall, 92.7% of individuals successfully completed the structured exercise therapy program. The high success rate was likely due to improvements in PROs and glenohumeral joint function without increases in tear size following exercise therapy (Table 4.3). A previous study investigating the effects of non-operative treatment in 452 individuals found that 15.0% failed before the conclusion of the 12-week program (30). Furthermore, a randomized controlled trial comparing operative and non-operative treatment in individuals with tears less than 3.0cm in size reported 5.9% of individuals failed prior to the conclusion of the 12-week program and elected for surgery (165). Ongoing follow-up is underway in the current cohort to investigate failure rates at 12-months and 2-years.

A limitation of the current study is the lack of healthy control data to determine if the changes observed in glenohumeral arthrokinematics restore the current individuals to a "healthy" status. Additional limitations included no assessment of other important factors (e.g. fatty infiltration) that may influence tolerance to exercise and tear propagation and the current study only included individuals with small tears isolated to the supraspinatus tendon and results should not be generalized to larger or more extensive tears. However, the objective of the current study was focused on the relative changes in glenohumeral joint function following a 12-week individualized exercise therapy program which was addressable given the current data.

4.1.5 Conclusion

The present study demonstrated that improved glenohumeral joint function and patient reported outcomes without increases in rotator cuff tear size occurred immediately following a 12-week individualized exercise therapy program. The small number of individuals that had an increase in tear size >5.0mm have a meaningful clinical implication such that the risk of tear progression following an individualized exercise therapy program was minimal.

5.0 Aim 2: Effects of a 12-Week Personalized Exercise Therapy Program

5.1 Improved Joint Function When Reaching Behind the Back is Associated with WORC Scores in Individuals with Rotator Cuff Tears Following Exercise Therapy

5.1.1 Introduction

Individuals with rotator cuff tears are generally prescribed non-operative treatment to improve pain and the ability to complete activities of daily living. Pain and restricted range of motion (ROM) when reaching behind the back has been reported in individuals with pathology of the shoulder (166, 167) and the American Shoulder and Elbow Surgeon (ASES) questionnaire includes questions regarding toileting, dressing and washing one's back (168). Pain related to rotator cuff pathology may also have central mechanistic changes affecting motor control and activation, leading to less joint stability due to decreased muscle function (133, 169, 170). This highlights the importance of understanding the relationship between patient reported pain and function and experimentally measured glenohumeral joint function when reaching behind the back.

A tear involving the supraspinatus tendon may elicit pain as the hand behind the back position has been shown to maximally stretch the supraspinatus (171). Posterior capsule tightness may contribute to pain and restricted motion as the posterior-inferior capsule is stretched during internal rotation and abduction. Exercise therapy has been shown to improve ROM and pain, which may improve an individual's ability to internally rotate and reach behind the back (31-33, 172). In-vivo kinematics of healthy individuals in static positions with the hand behind the back at the

L4-L5 vertebral level and when reaching maximally behind the back were previously reported (43). The motion of healthy individuals utilizing bone pins (44) and electromagnetic tracking (45) were investigated to quantify the amount of scapulothoracic motion and shoulder internal rotation when reaching behind the back. Although these studies provide a baseline for comparison, changes in glenohumeral kinematics following exercise therapy in individuals with rotator cuff tears when reaching behind the back remains unclear.

The overall objective of the study was to identify factors associated with changes in patient reported outcomes (PROs) following a 12-week exercise therapy program for individuals with symptomatic isolated supraspinatus tears. Additional objectives included determining the relationship between changes in passive glenohumeral internal rotation ROM and maximum glenohumeral internal rotation when reaching behind the back to determine if simple clinical measurements relate to dynamic function. Relative changes in passive ROM, glenohumeral kinematics and patient reported outcomes were also determined following exercise therapy. It was hypothesized that following a 12-week individualized exercise therapy program supervised by a physical therapist when reaching behind the back: 1) maximum glenohumeral internal rotation will increase and 2) contact path length will decrease. Furthermore, following exercise therapy, passive glenohumeral internal rotation ROM will increase and will positively correlate with maximum glenohumeral internal rotation when reaching behind the back, and changes in PROs will positively correlate with changes in maximum glenohumeral internal rotation and negatively correlate with contact path length when reaching behind the back.

5.1.2 Methods

5.1.2.1 Subjects

Eighty-four individuals (mean age 60.0 ± 9.4 years, mean BMI 28.4 ± 5.0 kg/m^2, 43 females) were recruited to participate in this prospective longitudinal observational study and provided IRB-approved written informed consent prior to performance of any research procedure. Only 84 of the 109 individuals in the cohort were utilized based upon the available and usable in-vivo kinematic data, lost to follow-up, etc. Individuals were included in the study if they had a symptomatic partial- (>50% thickness) or full-thickness rotator cuff tear isolated to the supraspinatus tendon, were 40 years of age or older, had a BMI <40 kg/m^2 and had at least 110° range of humerothoracic elevation. Individuals were excluded if they had a work-related injury, an asymptomatic tear, severe capsular tightness (<30° of internal or external rotation), or diabetes mellitus.

5.1.2.2 Description of Exercise Therapy Program

Participants underwent a 12-week physical therapist-supervised individualized exercise therapy program (12-visits in total), for non-operative treatment of a rotator cuff tear at the University of Pittsburgh Physical Therapy Clinical and Translational Research Center. The program utilized individualized criteria related to the participant's pain, ROM and strength to tailor the interventions to each individual's unique clinical presentation (173). The overarching framework focused on restoring passive glenohumeral ROM and strengthening of the rotator cuff and scapular muscles. However, depending on the initial staging of the individual based on tissue irritability, the impairments that needed to be addressed, and response to treatment, the selection and progression of interventions were individualized (158).

Range of motion, stretching exercises, and joint mobilization were performed as necessary to restore normal passive glenohumeral ROM. As ROM was restored, achievement of clinical criteria determined when interventions that focused on increasing strength of the rotator cuff and scapular muscles and task specific activities were initiated. Three levels of clinical decision-making led to the selection of individual specific interventions during each visit. The first level dealt with determining the stage at which the individual presented. Information regarding the pain-restriction sequence assisted the clinician in placing the individual in either the highly irritable, intermediate irritability or low irritability stage.

Second level decision making related to determining if passive and/or active ROM was restricted. Restricted ROM led the clinician to determine the cause as either limited accessory motion or loss of tissue extensibility and appropriate interventions were delivered. The final level of assessment made was the presence of weakness to determine the appropriate resistance and functional exercises. Exercise resistance and number of repetitions were determined based on a modification of the daily adjustable progressive resistance exercise program (174).

5.1.2.3 Measurement of Glenohumeral Kinematics

Glenohumeral kinematics were measured using a synchronized biplane radiography system at 50 images/second. To assess glenohumeral kinematics, individuals were seated with the involved glenohumeral joint centered in the system and performed a reaching behind the back movement (Figure 5.1). The only instructions provided to the individual were to keep their back straight, start with the hand on the thigh and reach behind the back. Three trials of the movement were performed before and after the exercise therapy program. For each test day, the trial in which the individual achieved the most glenohumeral internal rotation at any point throughout the movement was used for all analyses. Biplane radiographs were distortion corrected and the imaging system was calibrated following established procedures (31, 32, 35).

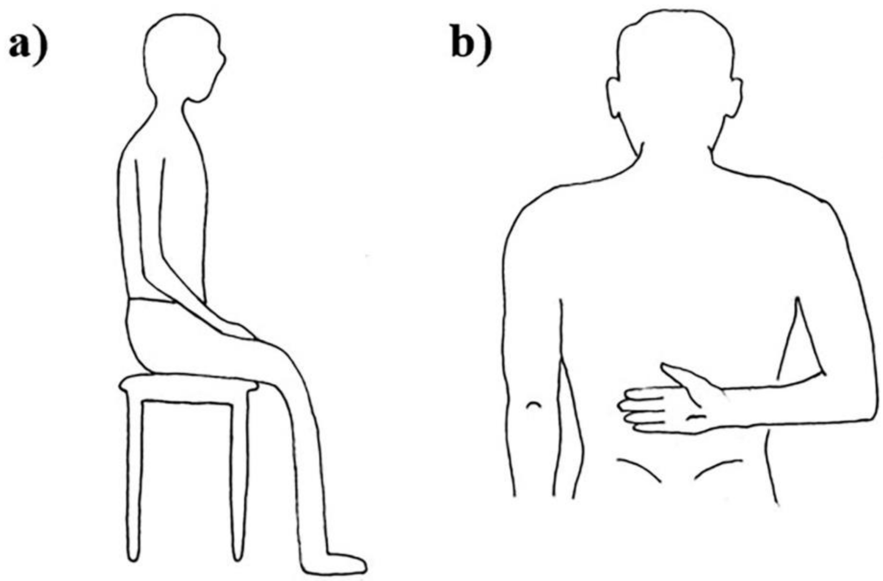

Figure 5.1: Schematic demonstrating the a) starting position with the affected side hand on the thigh and b) ending position of the reaching behind the back movement (adapted from Matsen FA III, Lippitt SB, Sidles JA, and Harryman DT II: Practical Evaluation and Management of the Shoulder. Philadelphia: WB Saunders, 1994.)

Individuals underwent a computed tomography scan of the involved shoulder and images were segmented using MIMICS 20 (Materialise, Leuven, Belgium) to create individual-specific humerus and scapula bone models. Digitally reconstructed radiographs of the bone models were created from the CT-based bone models and the known geometry of the biplane radiography system. A semi-automated matching process was used to optimize the correlation between the digitally reconstructed radiograph bone models and the distortion-corrected radiographs for each pair of synchronized images throughout the movement (35) (Figure 5.2). This allowed determination of humeral head movement with respect to the glenoid.

The local coordinate system for each humerus was constructed based on the International Society of Biomechanics recommendations, with the origin located at the center of the humeral head (149). The scapula coordinate system was modified to create a glenoid based system to describe humeral motion with respect to the center of the glenoid (31). Rotations were quantified with an accuracy of ± 0.5° (35). For each data frame, a 3D distance map was calculated between the humeral head and glenoid surfaces. The centroid of the 3D distance map was then quantified as the weighted average of the closest 200mm^2 region between the humeral head and glenoid surfaces, and acts as an estimate of the contact center location (151) where the humerus articulates on the glenoid.

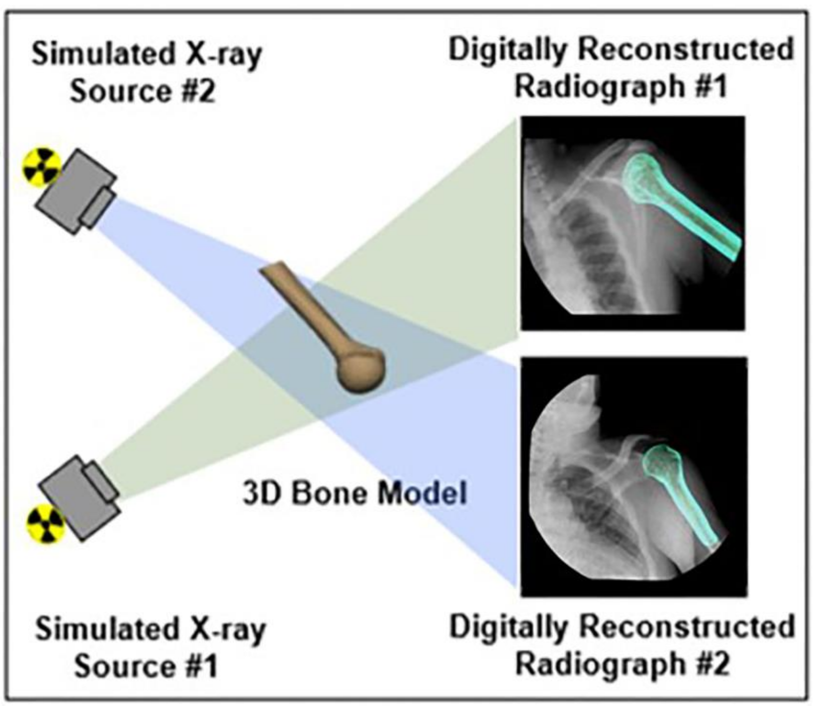

Figure 5.2: Visual representation of the validated registration process used to match individual-specific bone models to the dynamic biplane radiographs collected during a reaching behind the back movement.

Kinematic variables of interest included maximum glenohumeral internal rotation and the contact center location (150). Contact center data was normalized to glenoid AP width and SI height, allowing comparisons between individuals (150). The contact path length was calculated as the change in frame-by-frame position of the contact center providing an estimate of the distance the humeral head articulated on the glenoid surface. Since the contact center was normalized to glenoid AP width and SI height, the contact path length was normalized to glenoid size. A larger contact path length may indicate less joint stability due to less control of the humeral head on the glenoid surface. Due to variations in ROM between individuals, comparisons were made on an individual basis using the largest shared ROM between data collection sessions.

5.1.2.4 Measurement of Passive Range of Motion

Passive glenohumeral internal rotation ROM at 90° of humerothoracic abduction was measured by one of three certified physical therapists using a goniometer on the involved side with the individual in the supine position. The motion was stopped, and the measurement was recorded when the scapula tilted anteriorly. The position was chosen since it assesses posterior capsule tightness (128, 175) that may limit mobility when reaching behind the back. Previous literature has demonstrated intra- and inter-observer repeatability ranging from 0.62-0.84 and 0.62-0.86, respectively for goniometric measurement of glenohumeral internal rotation (176).

5.1.2.5 Patient Reported Outcomes

Study participants completed the ASES Shoulder Rating Scale (168) and the Western Ontario Rotator Cuff (WORC) Index (137). The ASES is a shoulder specific outcome measure that has demonstrated evidence of reliability, validity, and responsiveness for individuals with rotator cuff tears (138, 139). The WORC has also demonstrated reliability, validity, and responsiveness and is a rotator cuff specific outcome measure (138, 140, 141). Possible scores for both the ASES and WORC were from 0-100, where higher scores indicate greater function. The minimally clinical important difference for the ASES and WORC are 12.0 and 13.5, respectively (161, 162).

5.1.2.6 Statistical Analysis

An a priori sample size calculation conducted assuming a moderate effect size, $\alpha=0.05$ and $\beta=0.2$ determined 82 individuals were required to investigate the associations between glenohumeral kinematics and patient reported outcomes. Paired t-tests and Wilcoxon Signed Rank tests were utilized for normally and non-normally distributed data, respectively, to determine changes in variables following exercise therapy. Spearman's correlations were used to determine the relationships between variables. The Stuart-Maxwell test was utilized to determine differences between the pre- and post-exercise therapy distributions for all variables (177). The initial thresholds used to group the cohort were determined using quartiles for the respective pre-exercise therapy distribution resulting in thresholds with an equal number of individuals allowing for easier representation. The data were represented by a cross tabulation from before to after the exercise therapy program. As such, the diagonal of the matrix demonstrated the number of individuals who fell within the same category pre- and post-exercise therapy (green). The number of individuals above or below the diagonal represent those who improved (blue) or did not improve (red) depending on the variable. Significance was set to $p < 0.05$.

5.1.3 Results

All individuals completed the exercise therapy program and complete kinematic data was successfully collected for both the pre- and post-exercise therapy sessions. Overall, 93.0%, 66.0% and 92.0% of individuals successfully completed the WORC, ASES and passive ROM for both timepoints. When reaching behind the back, maximum glenohumeral internal rotation increased by 3.2 ± 8.6° (p=0.001, Table 5.1) and median contact path length decreased by 5.5% glenoid size (p=0.022) post-exercise therapy. In comparison to pre-exercise therapy, the relative increase in maximum glenohumeral internal rotation was 12.4% and decrease in contact path length was 13.5%. Passive glenohumeral internal rotation ROM increased by 4.9 ± 12.4° (9.7% increase in respect to pre-exercise therapy, p=0.001), WORC scores increased by 29.8 (p=0.001) and ASES scores increased by 21.1 (p=0.001). Overall, 74.4% and 60.0% of individuals improved by the minimal clinically important difference (MCID) or more for the WORC (MCID=13.5) and ASES (MCID=12.0), respectively (161, 162).

Table 5.1: Glenohumeral Kinematics, Passive Range of Motion and Patient Reported Outcomes

Measure	Pre	Post	p
Glenohumeral Kinematics			
Max. Glenohumeral Internal Rotation (°)	25.8 ± 13.9	29.0 ± 13.2	0.001*
Contact Path Length (% glenoid size)[a]	40.9 (25.9-55.3)	35.4 (22.2-48.0)	0.022*
PROM (involved side, °)			
Glenohumeral Internal Rotation@90	50.7 ± 14.4	55.6 ± 13.1	0.001*
Patient Reported Outcomes			
WORC Score[a]	60.1 (46.6-75.4)	89.9 (77.5-95.8)	0.001*
ASES Score[a]	69.3 (60.5-80.8)	90.4 (82.5-94.7)	0.001*

PROM, passive range of motion; WORC, Western Ontario Rotator Cuff; ASES, American Shoulder and Elbow Surgeons.

* Significant at p<0.05

[a] Data were non-normally distributed for at least one timepoint, Median (Interquartile Range)

Normally Distributed, (Mean ± SD)

No association was found between changes in passive glenohumeral internal rotation ROM measured at 90° of humerothoracic abduction and changes in maximum glenohumeral internal rotation measured via biplane radiography when reaching behind the back (ρ^2=0.03, p=0.117). No association was found between changes in the ASES score and changes in maximum glenohumeral internal rotation when reaching behind the back (ρ^2=0.06, p=0.071), however, a weak positive association was found between changes in the WORC score and changes in maximum glenohumeral internal rotation when reaching behind the back (Figure 5.3, ρ^2=0.09, p=0.008). Therefore, as changes in maximum glenohumeral internal rotation when reaching behind the back increased, WORC scores increased. No association was observed between changes in ASES scores and changes in contact path length (ρ^2=0.06, p=0.077), however, a weak negative association was found between changes in WORC scores and changes in contact path length (Figure 5.4, ρ^2=0.10, p=0.006). Thus, as changes in contact path length increased, WORC scores decreased.

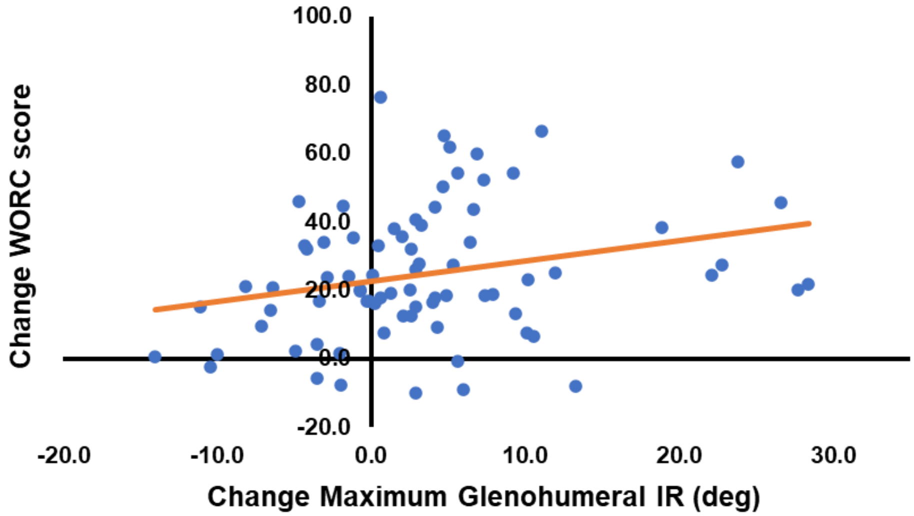

Figure 5.3: The association between changes in maximum glenohumeral internal rotation (IR) and WORC scores.

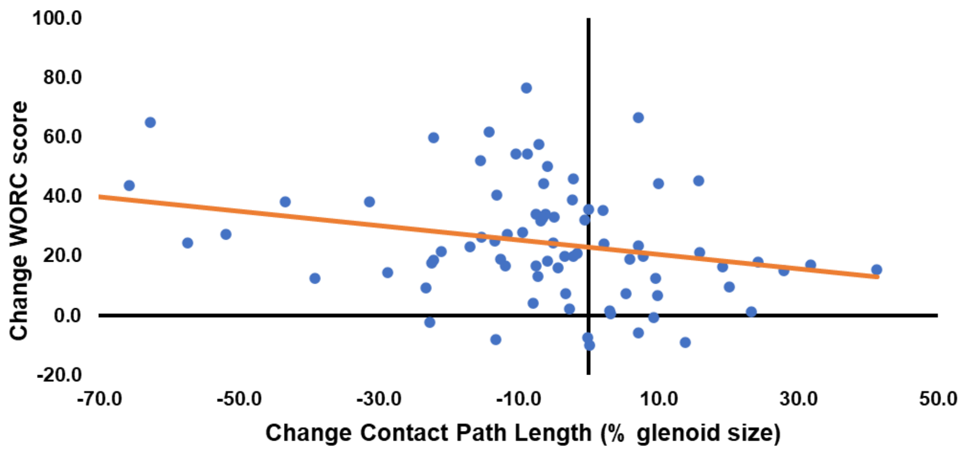

Figure 5.4: The association between changes in contact path length and WORC scores.

Significant changes in the distributions of all variables occurred post-exercise therapy (ranged p=0.001 to 0.034). The distribution of maximum glenohumeral internal rotation shifted towards increased values and the distribution of contact path length shifted towards decreased values. For both the ASES and WORC scores, the distributions shifted towards increased scores. Lastly, the distributions for passive glenohumeral internal rotation shifted towards increased ROM (Table 5.2 and Table 5.3, examples for WORC and ASES).

Table 5.2: Matrix representation of shift in distribution of WORC scores.

Post	Pre			
	0.0-≤47.0	>47.0-≤60.0	>60.0-≤75.0	>75.0
0.0-≤47.0	2	0	0	0
>47.0-≤60.0	0	4	0	0
>60.0-≤75.0	5	3	3	0
>75.0	12	13	17	18

Table 5.3: Matrix representation of shift in distribution of ASES scores.

Post	Pre			
	0.0-≤61.0	>61.0-≤69.0	>69.0-≤81.0	>81.0
0.0-≤61.0	1	2	0	0
>61.0-≤69.0	0	1	2	0
>69.0-≤81.0	0	1	1	2
>81.0	12	11	10	11

5.1.4 Discussion

Major findings from the current study demonstrated that after exercise therapy there was: 1) Improved maximum glenohumeral internal rotation when reaching behind the back and passive glenohumeral internal rotation ROM at 90° of humerothoracic abduction, 2) decreased contact path lengths when reaching behind the back, 3) no relationship between the changes in passive glenohumeral internal rotation at 90° of humerothoracic abduction and changes in maximum glenohumeral internal rotation when reaching behind the back, 4) a positive association between changes in maximum glenohumeral internal rotation when reaching behind the back and changes in WORC scores, and 5) a negative association between changes in contact path lengths when reaching behind the back and changes in WORC scores.

The first hypothesis that maximum glenohumeral internal rotation when reaching behind the back movement would increase post-exercise therapy was supported by the results. Following exercise therapy, maximum glenohumeral internal rotation when reaching behind the back was 29.0 ± 13.2°, which is comparable to results found in healthy individuals (≈30.0°) over the age of 45 years during a static hand behind the back position (43). The implication of this finding is that exercise therapy was successful in restoring glenohumeral internal rotation in individuals with a symptomatic isolated supraspinatus tear to a level comparable to "healthy" individuals. This may improve these individuals' ability to complete activities of daily living such as reaching into their back pocket.

The reasons for increased maximum glenohumeral internal rotation post-exercise therapy is likely multifactorial. Although passive glenohumeral internal rotation ROM increased post-exercise therapy, the current study found no association with maximum glenohumeral internal rotation measured via biplane radiography. Passive measures of internal rotation may not provide insight on active range of motion in-vivo during this movement, however, the two measurements were taken in different shoulder positions which changes the stress on the glenohumeral capsule and thus the amount of internal rotation. Limitations in reaching behind the back has been shown to not be strictly due to loss of glenohumeral internal rotation ROM (178), which may also explain why no association was observed. Furthermore, the individuals recruited in this study did not present with severe capsule tightness indicated by having more than 30° of internal and external rotation.

A positive association was found between changes in maximum glenohumeral internal rotation when reaching behind the back and changes in WORC scores, potentially indicating that an individual's active range of motion achieved or ability to reach behind the back plays a role in their perception of pain and function. In individuals with supraspinatus tears, this movement commonly evokes pain limiting their function (179) and is likely due to the position maximally stretching the supraspinatus (171). This finding is unique as previous work concluded that self-reported outcomes may be more influenced by pain relief and psychosocial factors such as patient expectation or mental health and not joint kinematics (155, 180, 181). However, pain relief and psychosocial factors likely accounted for some variability in the change of self-reported outcomes in the current study beyond that accounted for by changes in glenohumeral kinematics. Overall, the association between variables makes sense given patient reported outcomes such as the ASES specifically include questions regarding activities of daily living that require an individual to reach behind their back such as washing or fastening a bra (168).

The hypothesis that contact path length would decrease post-exercise therapy was also supported by the results. Decreased contact path length may imply more joint stability post-exercise therapy as there is less movement of the humeral head on the glenoid. Decreased contact path lengths may be due to improvements in subscapularis, infraspinatus and teres minor muscle strength observed post-exercise therapy in this cohort (unpublished data from laboratory). Improvements in isometric muscle strength of the subscapularis, infraspinatus and teres minor likely improved the efficacy of the transverse and coronal plane glenohumeral force couples that have been shown to maintain joint stability in the presence of an isolated supraspinatus tear (20).

The contact path length data in the literature based on movements in healthy individuals can put the results of the current study in perspective. The contact path length was 31.6 ± 11.0% glenoid height (range 17.2% to 58.8%) during coronal plane abduction in aged-matched controls between the range of 20° to 70° of glenohumeral elevation (33). The individuals in the current cohort experienced comparable magnitudes of contact path length post-exercise therapy when reaching behind the back, which is a complex movement. Future work to obtain contact path length data in healthy individuals when reaching behind the back is needed to make a more direct comparison.

Positive changes in contact path lengths were associated with negative changes in WORC scores, which suggests that an individual's perception of pain and function may be influenced by joint stability. Pain related to the rotator cuff has been shown to induce central mechanistic changes potentially affecting motor control (133, 169). Thus, improvements in pain observed in this cohort may have improved muscle function, and/or the reduced pain allowed the individuals to complete the movement in a more comfortable manner. The number of individuals who achieved the MCID was lower than those who improved without achieving the MCID. The discrepancy may be due to the fact that 25.6% of individuals had WORC scores >60.0 and ≤75.0 and 23.1% had WORC scores >75.0 pre-exercise therapy. Due to the higher pre-exercise therapy scores, the MCID may be more difficult to achieve, potentially indicating MCIDs should be adjusted depending on the pre-exercise therapy score.

The current study indicated that exercise therapy may influence various outcome parameters depending on an individual's pre-exercise therapy status. For example, Table 5.2 demonstrates the most frequent shift observed was 17 individuals who began exercise therapy with a WORC score >60.0 and ≤75.0 but ended the program with a score >75.0. The representation of this data is novel and is useful clinically as it provides insight on who may experience improvements given their initial status.

A limitation of the study is the lack of control individuals to determine if the observed changes in contact path length return the individuals in this cohort to "normal". Additionally, the vertebral level these individuals were able to reach was not assessed, preventing some comparisons to previously published work (179). However, the current study demonstrated the relative changes in glenohumeral joint function during a novel movement, as well as the relationships with PROs following a 12-week individualized exercise therapy program. Future studies investigating changes in joint function in individuals with large rotator cuff tears should consider utilizing this movement given its applicability to activities of daily living and potential use in predicting outcomes of exercise therapy.

5.1.5 Conclusion

The implications of the present study were that the movement of reaching behind the back was useful to assess associations between glenohumeral joint function and PROs in individuals with rotator cuff tears. Following exercise therapy, glenohumeral internal rotation improved to similar levels of healthy individuals and improvements in joint stability and PROs were observed, where WORC scores were associated with the observed in-vivo changes. These unique findings provide new information to clinicians regarding changes following exercise therapy in individuals with rotator cuff tears and targetable factors during treatment that may result in improved patient reported outcomes.

6.0 Aim 3: Differences in Joint Stability Between Individuals that Underwent Exercise Only or Exercise Followed by Surgery: A Computational Study

6.1 Validation of Subject Specific Models to Determine Changes in Joint Stability Following Exercise Therapy in Individuals with Symptomatic Rotator Cuff Tears

6.1.1 Introduction

The effects of exercise therapy for individuals with rotator cuff tears on patient reported outcomes (PROs), range of motion (ROM), isometric muscle strength and glenohumeral kinematics have been investigated (30-33). Factors such as "in-vivo muscle forces" and the magnitude and direction of the joint reaction force are also important to determine following exercise therapy as they provide information on the ability for the musculature to center the humeral head on the glenoid. However, these in-vivo muscle forces cannot be directly measured. A common solution to this problem is utilization of computational models to predict muscle forces and joint reaction forces throughout a movement. Previous models that were developed to perform simulations of the shoulder complex include the MoBL-Arms model, the Swedish model, the Newcastle model, the Delft Shoulder and Elbow model (47-50, 61, 182-185). Overall, previous computational models have established the groundwork for modeling the glenohumeral joint and proved to be useful in estimating muscles forces and joint reaction forces.

However, for studies that investigate rotator cuff tears using computational models, the supraspinatus muscle-tendon unit is generally not included and not modeled according to the actual pathology (i.e. partial- or full-thickness) (23, 186). Replication of the injury state is important because the net sum of forces crossing the glenohumeral joint could be affected by assumptions made during the model processing. Furthermore, most models lack accurate implementation of scapular kinematics due to the use of marker-based motion tracking to drive the motion of the models. Specifically, during activities of daily living such as abduction, the scapula rotates and translates beneath the skin surface which cannot be adequately tracked with reflective markers attached on the skin. Furthermore, some models implement regression models previously determined to define how the scapula moves based on the position of the humerus (187). This methodology is also problematic as the regression models were developed using a small sample of 10 subjects, but even more importantly the subjects were described as having no shoulder complaints. Thus, the regression models may not accurately represent scapulothoracic kinematics in individuals with rotator cuff tears since scapular dyskinesis has been shown in individuals with shoulder pathology (175, 188). The inability to accurately track the scapula will change the line of action of muscles within simulations inducing systematic error. Lastly, computational studies have compared individuals with rotator cuff tears to healthy controls (23), but have not investigated changes in joint function following exercise therapy. Quantification of the changes in joint stability following exercise therapy will allow identification of individuals that did not respond to the exercise therapy who may need additional treatment including surgery.

To be confident in the results of a computational model and investigate changes in joint function following exercise therapy, a series of validation steps should be conducted to provide evidence that the model is producing reasonable results. Based on the recommendations in the literature and general modeling practices, validation criteria were developed pertaining to the simulated kinematics, joint reaction forces and muscle function. The model outputs were then tested against the criteria the to determine if realistic outcomes were obtained (93). Thus, the objective of the current study was to construct and validate novel subject specific models of the glenohumeral joint for individuals with rotator cuff tears to quantify the magnitude of the joint reaction force. The following validation criteria were utilized: 1) the model will be able to replicate anatomical landmark locations within 5.0mm and joint angles within ±0.5° (accuracy of system used to experimentally measure in-vivo kinematics), 2) the magnitude of the joint reaction forces will be within 2 standard deviations of previous modeling, cadaveric and instrumented implant studies, 3) muscle moment arms included in the model will be within 2 standard deviations of the literature and follow similar trends, and 4) simulated muscle activation will be similar to previous literature.

6.1.2 Methods

6.1.2.1 Subjects

Twelve subjects (7 females and 5 males, 57.9 ± 10.9 years, BMI 26.8 ± 5.8 kg/m^2) were recruited to participate in this prospective observational study and provided IRB-approved written informed consent prior to performance of any research procedure. Individuals were included in the study if they had a symptomatic partial- (>50% thickness) or full-thickness rotator cuff tear isolated to the supraspinatus tendon, were above the age of 40, had a BMI <40 kg/m^2 and had at least 110° range of humerothoracic elevation. Individuals were excluded if they had a work-related injury, an asymptomatic tear, severe capsular tightness (<30° of internal or external rotation), or diabetes mellitus.

6.1.2.2 Exercise Therapy Program

All individuals underwent a 12-week personalized exercise therapy program for treatment of rotator cuff tears as previously described in Section 4.1.2.3. Briefly, the program utilized specific individualized criteria related to the study participant's pain, ROM and strength to tailor the interventions to each individual's unique clinical presentation (157). The overarching framework focused on restoring passive glenohumeral ROM and strengthening of the rotator cuff and scapular muscles. However, depending on the initial staging of the individual based on tissue irritability, the impairments that needed to be addressed, and response to treatment, the selection and progression of interventions were individualized (158).

6.1.2.3 Quantifying Glenohumeral Kinematics

Glenohumeral kinematics during scapular plane abduction were measured pre- and post-exercise therapy using a synchronized biplane radiography system at 50 images/second as previously described in Section 4.1.2.7. The collected biplane radiographs were distortion corrected and the imaging system was calibrated following established procedures (31, 32, 35). Digitally reconstructed radiographs of the bone models were created from the CT-based individual specific bone models and the known geometry of the biplane radiography system.

A semi-automated matching process was used to optimize the correlation between the digitally reconstructed radiographs and the distortion-corrected radiographs for each pair of synchronized images throughout the movement (35). Rotations were quantified with an accuracy of ± 0.4mm and ± 0.5°, respectively (35). Utilizing this process, three bony anatomical landmarks on the humerus (center of humeral head, medial and lateral epicondyles) and scapula (trigonum scapulae, angulus acromialis, angulus inferior) were digitally tracked throughout the movement. The relationship between the landmarks and anatomical coordinate system of each bone are known, allowing identification on the bone models in OpenSim.

Thus, the experimental in-vivo data was used to position the bones and drive the model's motion. The accuracy for replicating the position of the bony anatomical landmarks in the simulation was determined by calculating the average and maximum error compared to the known experimental locations throughout the simulation. Furthermore, a X-Y-Z Euler angle rotation sequence was constructed using the experimentally known anatomical landmarks and simulated anatomical landmarks. The average difference in abduction, internal-external rotation and flexion-extension throughout the movement was compared using the two sets of joint angles to validate the kinematics were within the accuracy of the experimental testing system.

6.1.2.4 Individual Specific Muscle Parameters

The supraspinatus, infraspinatus, subscapularis, teres minor and middle deltoid geometries were created using MIMICS 20 (Materialise, Leuven, Belgium) and the pre-exercise therapy computed tomography images similarly to previous work (189-191). The geometries were then imported into MeshLab (v2022.02) as STL files and muscle volume was determined for the rotator cuff and middle deltoid muscles using the compute geometric measures operation (192). Intra- and inter-observer repeatability for determining muscle volume was determined to be $1.0cm^3$ and $0.9cm^3$, respectively. Based on the repeatability data and the previously published equation for determining maximum isometric force (23), the largest variability in estimating isometric force would be approximately 7.5N. The maximum isometric force each muscle could produce was based on muscle volume as individualizing muscle forces has been shown to influence predicted joint contact forces and was calculated as previously described (23).

For the supraspinatus, infraspinatus and subscapularis, three muscle-tendon units were utilized, whereas one muscle-tendon unit was utilized for both the teres minor and middle deltoid. Specifically, a muscle-tendon unit refers to a line of action for a muscle in the model and this terminology will be used throughout the study. Three muscle-tendon units were utilized for the supraspinatus to model the anterior, middle and posterior muscle-tendon portions, allowing implementation of tear size and location to further individualize the computational models. Furthermore, three muscle-tendon units were used for the subscapularis and infraspinatus as they are broader muscles with wide attachments. Additionally, different sections of the subscapularis and infraspinatus have been shown to have different function (7, 193). Constructing the models in this manner also allows for consistent implementation of tear characteristics if the tear were to propagate into neighboring tendons. The maximum isometric force each muscle could produce was then evenly distributed among the muscle-tendon units. For example, if the subscapularis was able to produce 600N, the maximum isometric force for each muscle-tendon unit would be 200N. For the supraspinatus, the same method was used, however, an additional step was performed to scale the maximum isometric force for each unit based on the amount of tendon torn (Section 6.1.2.6).

Isometric muscle strength was also measured pre- and post-exercise therapy by a licensed physical therapist in four joint positions including: 1) external rotation with the arm at the side, 2) internal rotation with the arm at the side, 3) external rotation at 90° of abduction in the coronal plane, and 4) scapular plane abduction at 90° of humerothoracic abduction. A handheld dynamometer (Lafayette Manual Muscle Testing System, Lafayette Instrument Company, Lafayette, IN) was used to make three measurements on the involved side for each joint position and the average of the three measurements was determined. The repeatability for assessing shoulder strength in symptomatic individuals has been shown to be excellent, with intra-observer repeatability of 0.85 (internal rotation) and 0.92 (external rotation) and inter-observer repeatability of 0.85 (internal rotation) and 0.82 (external rotation) using a handheld dynamometer (135).

To further individualize the model, the ratio of the change in isometric strength was determined (post-exercise therapy strength value divided by pre-exercise therapy strength value) for each joint position. The maximum isometric force for each muscle determined using muscle volume (pre-exercise therapy) was scaled by the ratio change in isometric strength to determine post-exercise therapy values. For example, the ratio change in internal rotation strength with the arm at the side was used to scale the maximum isometric force of the subscapularis following exercise therapy. Since exercise therapy did not include exercises targeting the deltoid, the maximum isometric force was kept constant from pre- to post-exercise therapy. Thus, the current models incorporate individual specific changes in muscle strength following exercise therapy.

6.1.2.5 Muscle Lines of Action

The lines of action of the muscle-tendon units were determined using a custom written MATLAB (R2020a, MathWorks, Natick, Massachusetts) code. The code imported the individual specific bony and muscle geometries that were segmented from the computed tomography images. Utilizing the geometries and the known relationships between the anatomical coordinate systems, the origins and insertions of each muscle could be determined in the scapula and humerus coordinate system, respectively. For muscle-tendon units with three compartments, the width of the origin/insertion was split into three equal sections, and the geometric center of each section was taken as origins or insertions. For muscles with one muscle-tendon unit, the geometric center of the entire origin/insertion was taken as the origin or insertion (93). To demonstrate this method was reasonable, the moment arms for each muscle will be compared to previous literature (see Section 6.1.2.8).

6.1.2.6 Measuring Rotator Cuff Tear Characteristics

Ultrasound was used to quantify the anterior-posterior (AP) tear size within the supraspinatus tendon. Assessments were performed with a 6-15 MHz linear array transducer (LOGIQE9, General Electric, MA) by a musculoskeletal radiologist. Individuals were seated with the glenohumeral joint in extension, and the involved side hand on the iliac wing to expose the supraspinatus tendon (142, 143). Tear size was quantified as the AP distance of the tear measured perpendicular to a line tangent to the posterior edge of the long head of the biceps tendon. Tear location was quantified as the AP distance measured perpendicular to a line tangent to the posterior edge of the long head of the biceps tendon to the most anterior tear edge. Tear thickness was quantified as the thickness of the tear in the superior-inferior direction measured perpendicular to the superior facet divided by the entire superior-inferior thickness of the tendon measured perpendicular to the superior facet. Diagnostic ultrasound has high sensitivity and reliability for detection and quantification of rotator cuff tears with accuracy on the order of 1.0mm or less (144-148). The width of the superior facet was also measured based on the individual specific humerus bony geometry.

The maximum isometric force for each supraspinatus muscle-tendon unit was then scaled based on the amount of tendon torn. For example, perhaps the maximum isometric force the supraspinatus as a whole could produce was 300N, and the tear characteristics were a full-thickness tear measuring 10mm, tear location of 0mm and superior facet length of 30mm. Given this information, each tendon portion theoretically has a width of 10mm (0→10mm is anterior portion, 10→20mm middle portion, 20→30mm posterior portion) and the tear is 10mm in length and full thickness. Thus, the entire anterior portion is torn and cannot transmit force to the humeral insertion. Since the tear does not extend past the anterior portion, the middle and posterior portions would each have a maximum isometric force of 100N. If the tear was partial-thickness in this hypothetical example, the maximum isometric force the anterior unit could produce would be 100N * (1 - minus the tear thickness ratio).

6.1.2.7 Computational Modeling Workflow

The experimentally measured in-vivo kinematics acted as the input to drive the models for pre- and post-exercise therapy timepoints, where inverse kinematics was used to minimize the sum of the squared error between the experimental and simulated anatomical landmarks. The resulting motion was utilized to determine the muscle forces at each step of the simulation (static optimization, an extension of inverse dynamics) and muscle-tendon units were assumed to be ideal force generators. Thus, force-length and force-velocity relationships were ignored. Previous work has shown this simplified approach is similar to approaches using force-length and force-velocity relationships during gait (194). Furthermore, in the presence of a rotator cuff tear, the aforementioned relationships may change due to degenerative changes which would introduce additional unknowns and further supports the simplified approach. The objective function minimized the sum of muscle activations squared. Lastly, joint reaction force analysis was utilized to determine the resultant forces at the glenohumeral joint.

6.1.2.8 Outcome Parameters and Validation Criteria

Primary outcome parameters were the simulated anatomical landmarks for inverse kinematics, magnitude of the joint reaction force, muscle moment arms and muscle activation (quantified as force/maximum isometric force) throughout scapular plane abduction. Validation criteria for the output parameters are shown in Figure 6.1. Briefly, the error in simulating the known experimental anatomical landmarks and kinematics was determined to ensure the simulation is appropriately mimicking the experimental motion. Additionally, the magnitude of the joint reaction force and muscle moment arms should be within two standard deviations of the literature and follow similar trends. Lastly, muscle activation or timing should be qualitatively similar to previous literature (93). Previous studies have utilized data in the literature to ensure muscle moment arms and joint reaction forces were reasonable (23, 195-198). Descriptive statistics included means and standard deviations pre- and post-exercise therapy and continuous curves were also constructed to qualitatively compare the data to previous literature. For plotting variables such as moment arms throughout scapular plane abduction, the movement was normalized from minimum (0%) to maximum (100%) humerothoracic abduction.

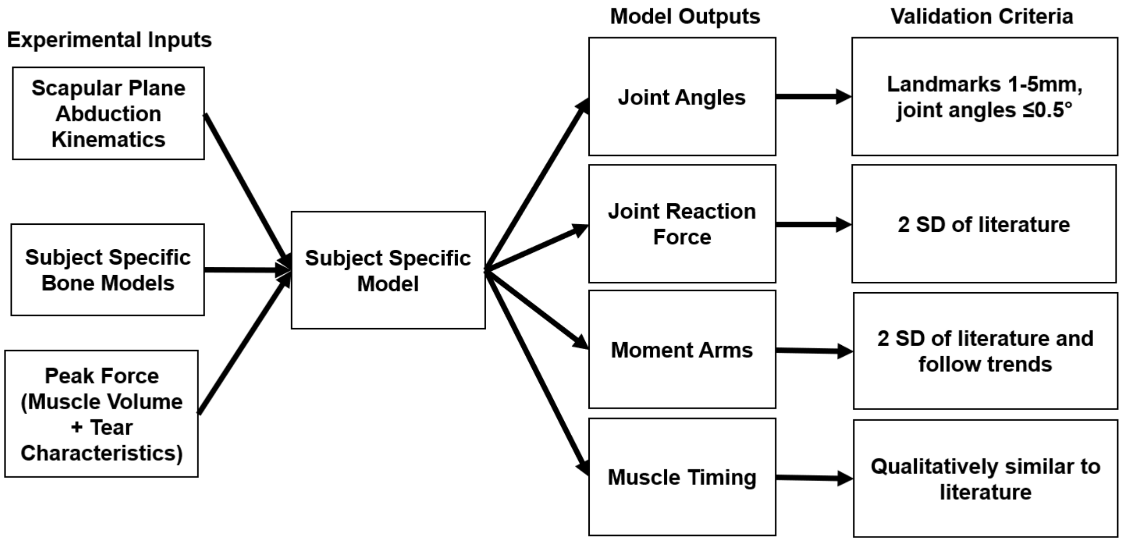

Figure 6.1: Modeling workflow, output parameters and validation criteria.

6.1.3 Results

The maximum error between the simulated and experimentally tracked anatomical landmarks for pre- and post-exercise therapy simulations was 1.8 ± 0.6mm (range 1.1-2.9mm) and 2.0 ± 0.6mm (range 1.1-2.9mm), respectively. Irrespective of the test day, this led to a difference of ±0.3° for rotations and ±1.1mm for translations between the simulated and experimental kinematics. The magnitude of the joint reaction force for pre- and post-exercise therapy were 0.66 ± 0.14*BW (range 0.39-0.87*BW) and 0.64 ± 0.15*BW (range 0.44-0.90*BW), respectively (Figure 6.2). For pre- and post-exercise therapy timepoints, the magnitude of the joint reaction force increased to a maximum and then decreased with increasing abduction in the scapular plane.

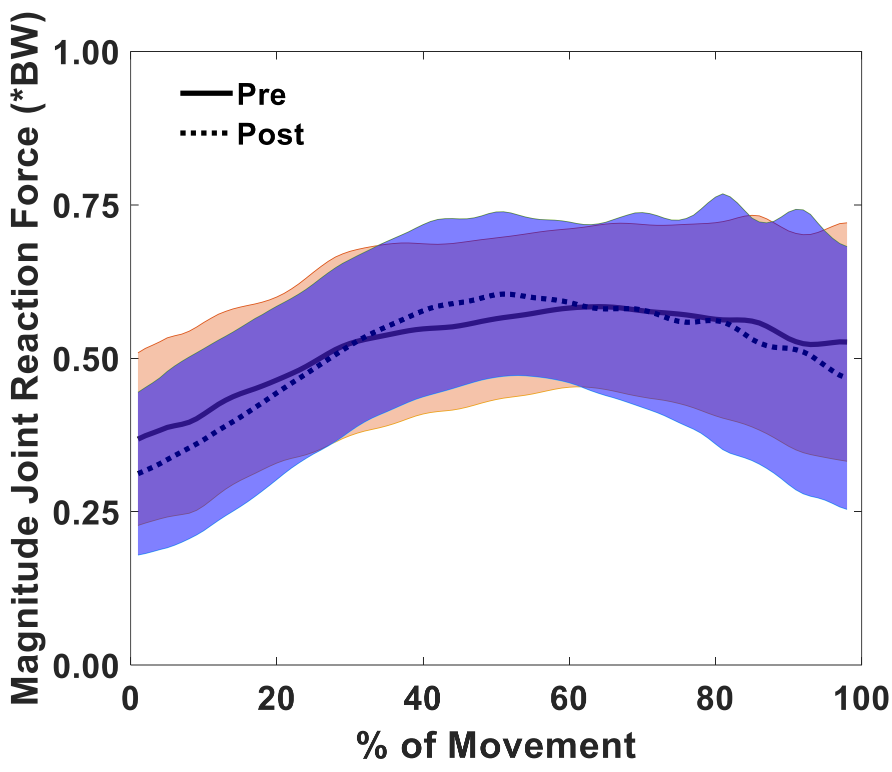

Figure 6.2: Average magnitude of the joint reaction force pre- and post-exercise therapy.

In regards to muscle moment arms, the maximum moment arm for each muscle in the current study and previous literature can be seen in Table 6.1 (7, 199-201). The middle deltoid's abduction moment arm decreased with increasing abduction, ranging from approximately 10.0-32.0mm and 2.0-31.0mm for pre- and post-exercise therapy, respectively. The supraspinatus moment arm remained relatively constant for both pre- and post-exercise therapy between approximately 17.0-24.0mm. Overall, the supraspinatus moment arm increased during the first 50% of the movement and then decreased with increasing abduction (Figure 6.3). The moment arm of the infraspinatus was similar pre- and post-exercise therapy ranging between 6.0-10.0mm and increased with increasing abduction. The moment arm of the subscapularis increased with increasing abduction ranging from approximately 4.0-15.0mm depending on the test day. For the teres minor, the moment arm increased with increasing abduction ranging between -6.0mm and -1.0mm, but remained an adductor for the entirety of the movement (Figure 6.4).

Table 6.1: Muscle moment arms pre- and post-exercise therapy from the current study and previous literature (mean ± standard deviation, mm).

	Pre	**Post**	**Literature**
Middle Deltoid	34.2 ± 5.0	32.0 ± 6.3	33.4 ± 3.7
Supraspinatus	23.6 ± 3.2	23.4 ± 3.2	26.4 ± 4.1
Infraspinatus	10.5 ± 3.7	10.4 ± 3.9	11.2 ± 7.6
Subscapularis	13.5 ± 6.2	15.1 ± 4.3	9.7 ± 2.5
Teres Minor	0.1 ± 4.6	0.5 ± 4.8	6.4 ± 5.2

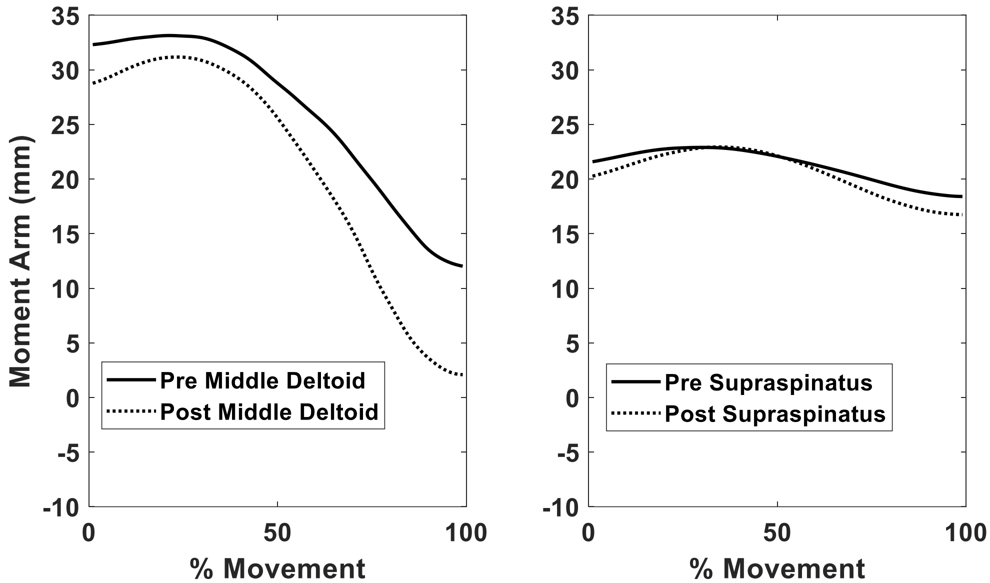

Figure 6.3: Average middle deltoid and supraspinatus moment arm during scapular plane abduction.

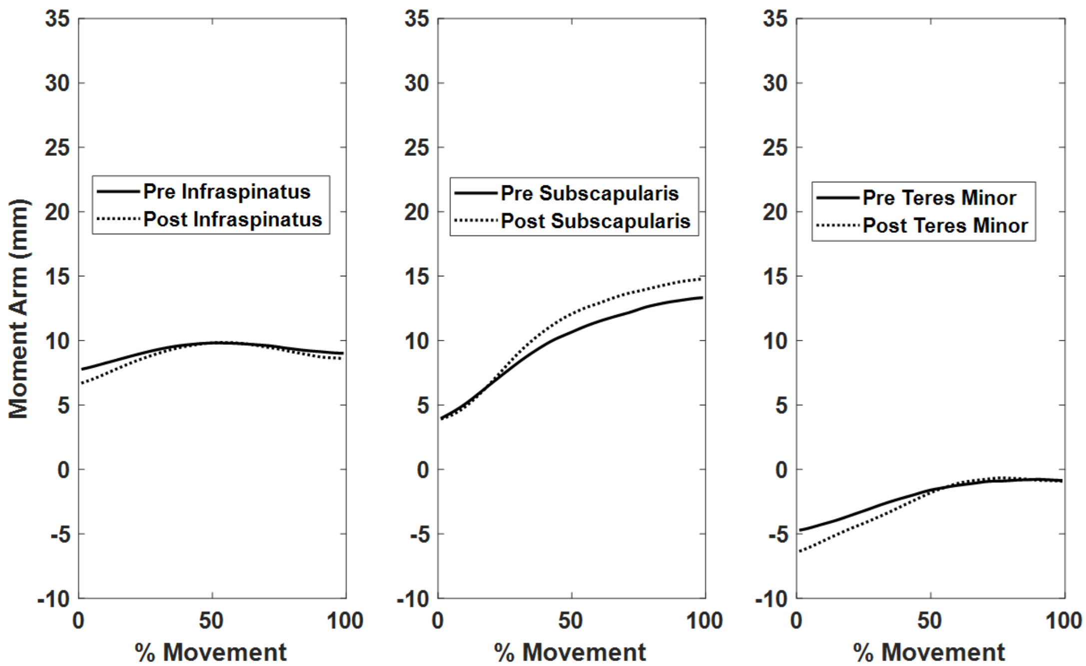

Figure 6.4: Average infraspinatus, subscapularis and teres minor moment arms during scapular plane abduction.

The activation level for all muscles remained below 0.40 regardless of the test day. The middle deltoid was most active at approximately 50% of the movement for pre- and post-exercise therapy. The middle deltoid's activity increased from 0-50% of the movement and then had decreased activity with increasing abduction. The middle deltoid appeared to be less active post-exercise therapy. The supraspinatus had very little activity throughout abduction but slightly increased with increasing abduction (Figure 6.5).

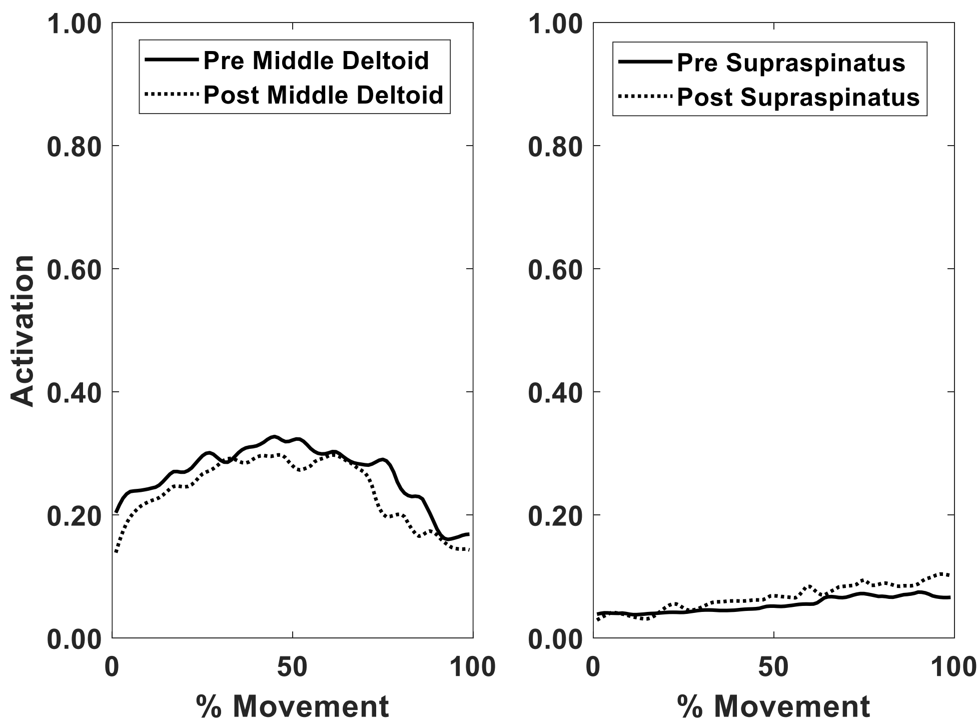

Figure 6.5: Average activation of the middle deltoid and supraspinatus during scapular plane abduction.

The activity of the infraspinatus remained relatively constant on both test days at approximately 0.1 (Figure 6.6). However, the activation of the infraspinatus prior to exercise therapy increased during 75-100% of the movement. The increase in activation during the last quarter of the movement was not observed post-exercise therapy. The activation of the subscapularis increased with increasing abduction on both test days but appeared to be slightly less active post-exercise therapy. Overall, the activation of the subscapularis ranged between approximately 0.1-0.4. Lastly, the teres minor was minimally active throughout abduction and remained below 0.1 activation on both test days.

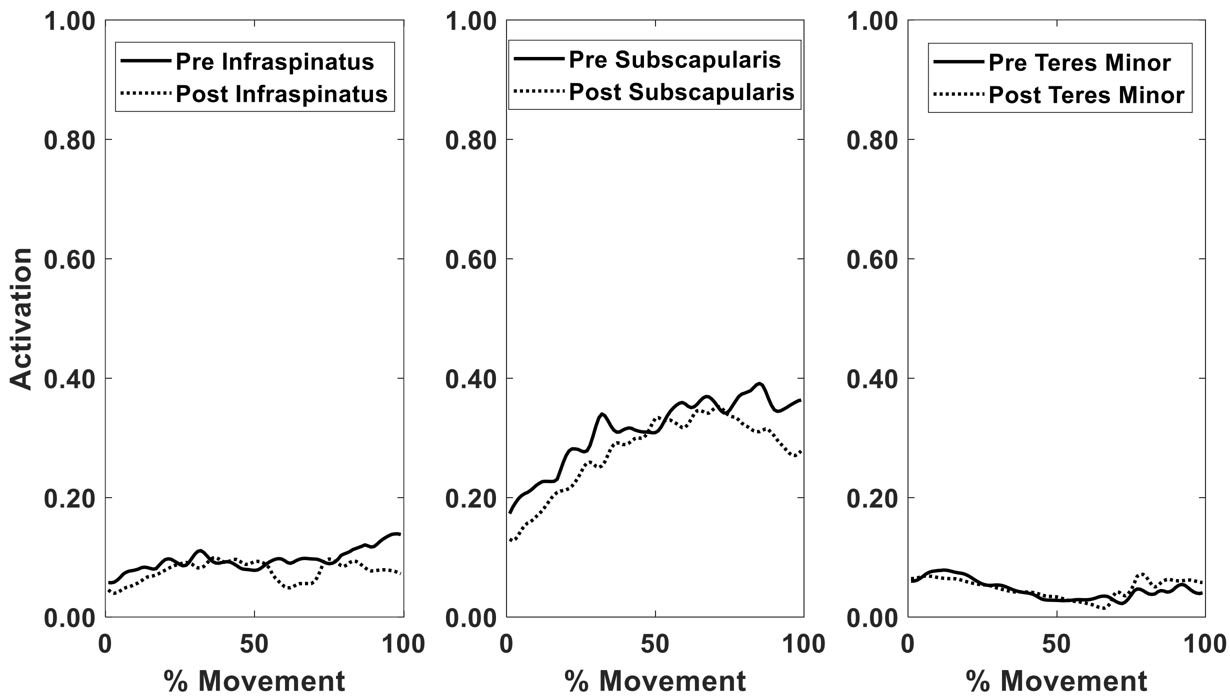

Figure 6.6: Average activation of the infraspinatus, subscapularis and teres minor during scapular plane abduction.

6.1.4 Discussion

The current study developed subject specific models of the glenohumeral joint for individuals with symptomatic isolated supraspinatus tendon tears that incorporated subject specific in-vivo kinematics, bony geometries, muscle parameters and tear characteristics. Outputs utilized for validation included the accuracy of the simulated kinematics, the magnitude of the joint reaction force, muscle moment arms and muscle timings. Regarding the accuracy of the simulated kinematics, the current study found the simulated anatomical landmarks were within 2.0mm and overall kinematics were within ±0.3°. Since the accuracy of the biplane radiography system is ±0.5° when determining glenohumeral kinematics (35), the simulated kinematics were within the accuracy of the testing system. Therefore, the differences are negligible and likely not clinically significant. Given the validation criteria in Figure 6.1, the model is reasonably replicating the experimental motion and the simulated motion was validated.

The magnitude of the joint reaction force was determined pre- and post-exercise therapy during scapular plane abduction and was found to range between 0.39-0.90*BW when considering both test days. Previous studies investigating the magnitude of the joint reaction force during abduction and no weight in hand observed values ranging between 0.43-0.90*BW (202-205). Thus, the findings of the current study were within the range of previously reported literature and met the validation criteria. Furthermore, the shape of the joint reaction force curve makes sense based on the anatomical function of glenohumeral joint and surrounding musculature. Between early abduction and approximately 90° of humerothoracic abduction, the middle deltoid and rotator cuff will be active to abduct and stabilize the glenohumeral joint, as well as counter balance the external moments (47). This results in an increase in the joint reaction force to a maximum occurring around 90° of humerothoracic abduction. Then, at higher levels of abduction, less force is required by the middle deltoid to abduct the humerus and upward rotation of the scapula provides bony support for the humeral head aiding the rotator cuff muscles that are providing stabilization. The shape of the magnitude of the joint reaction force curve does differ from experimental studies utilizing cadavers, which generally observe an increase in the magnitude with increasing abduction (20, 206). However, this is likely due to the scapula being rigidly fixed preventing upward rotation and higher levels of abduction.

Validation of the muscle moment arms is key as it provides support that the origins and insertions of the muscles determined using the computed tomography images were reasonable. Additionally, when assuming ideal generators, the moment arm in conjunction with the maximum isometric force influences the overall activity of each muscle since a muscle with a larger moment arm requires less force to produce a given moment. Thus, in some cases larger moment arms will be more cost effective to the optimization routine since the goal is to minimize the sum of the activations squared. Compared to experimental studies utilizing cadavers, all the muscle moment arms in the current study follow similar trends with increasing abduction with the exception of the middle deltoid. Previous studies found the moment arm of the middle deltoid increases or remains constant with increasing abduction and one study found it increased until 60° of abduction and then decreased with increasing abduction (199, 201, 207, 208). Discrepancies with some of the referenced experimental studies utilizing cadavers are likely due to the scapula being rigidly fixed, resulting in maximization of the deltoid's moment arm (20). Moment arms, by definition, were calculated as the distance from the muscles line of action to the joint center (209). Thus, changes in the scapula's orientation in respect to the thorax and changes in glenohumeral internal or external rotation will influence the middle deltoid moment arm. Therefore, the trend is biomechanically reasonable and make sense given the current model incorporates accurate in-vivo kinematics of the scapula. As for the rotator cuff muscles, the current study's trends agree with previous literature where the subscapularis and teres minor moment arms increase with abduction, while the supraspinatus and infraspinatus abduction moment arms remain relatively constant.

In regard to the magnitude of the moment arms, all of the muscle moment arms were within 2 standard deviations of previous literature and were validated (Table 6.1) with the exception of the subscapularis post-exercise therapy. The subscapularis moment arm was 0.4mm larger than 2 positive standard deviations above previous literature. However, the previous experimental studies only quantified the moment arms to 120° of humerothoracic abduction. Individuals in the current study had maximum values of humerothoracic abduction of 142.5 ± 23.1° (range 94.8-165.3°) post-exercise therapy. The subscapularis abduction moment arm was found to increase with increasing abduction in the current study, which is in agreement with previous reports (201, 210). Since individuals in the current study had greater levels of abduction, the slightly larger moment arm observed appears reasonable as it would be expected to increase with the increased abduction levels observed.

Regarding muscle activation, few studies have utilized electromyography to determine rotator cuff and deltoid muscle activity in individuals with rotator cuff tears during scapular plane abduction. However, one study investigated the activation of the infraspinatus and middle deltoid in individuals with rotator cuff tears (211). The activity of the infraspinatus increased between 0.0-40.0° of glenohumeral abduction and then remained relatively constant from 40.0-60.0° of glenohumeral abduction. In regard to the shape of the curve, the current study found similar results. Furthermore, the middle deltoid was found to increase with abduction from 0.0-60.0° of glenohumeral abduction (211). In the current study, the middle deltoid was increasingly active until approximately 50% (72.2 ± 14.9° glenohumeral abduction) of the movement and then decreased with increasing abduction. The shape of the curve is also consistent with findings from previous computational models during abduction when considering activation was calculated as the force produced divided by the maximum isometric force the muscle can produce (47).

Conflicting evidence exists regarding differences in activation of the subscapularis between healthy controls and individuals with rotator cuff pathology (212). Furthermore, reports suggest no differences between teres minor activation between healthy controls and individuals with rotator cuff pathology (212). Thus, the findings of the current study were compared to electromyography data in healthy controls. Activation of the subscapularis in the current study increased with increasing abduction and slightly decreased as maximum abduction was achieved. The results observed are in agreement with previous findings (213). Activation of the teres minor remained low and relatively constant with increasing abduction in the current study, whereas previous literature demonstrated an increase in activation that plateaued towards maximum abduction (213). The observed discrepancy may be related to the amount of glenohumeral external rotation during the movement at higher abduction angles, as well as the method used to normalize activation.

Lastly, due to the incorporation of supraspinatus tear size, location and thickness and the optimization routine used to determine muscle forces, no comparisons can be made regarding the activation of the supraspinatus. Specifically, the optimization routine utilizes the moment arms and maximum isometric force of each muscle while minimizing the sum of the activation squared. Since the maximum isometric force decreased based on the subject specific tear characteristics, maximal usage of the supraspinatus would come at a high cost given its decreased force potential. Thus, the activation in the current simulations is not like experimental studies where magnitudes of the muscle activation may be similar even if the force produced cannot be transferred through the tendon.

A limitation of the current study is the lack of experimental electromyography data to directly validate the activation results obtained from the simulation. However, based on findings from previous reports, comparisons were made that provided support that the trends observed were reasonable during scapular plane abduction given the modeling techniques. Another limitation was the assumption that the muscle-tendon units were ideal generators (ignored force-length-velocity relationships). The assumption that the muscles were ideal generators was preferred as determining these relationships is difficult on a subject specific basis, especially in the presence of a rotator cuff tear. Furthermore, including those relationships increases the complexity and number of unknowns. This approach has also been shown to be similar to approaches using force-length and force-velocity relationships during gait (194). Future studies will conduct sensitivity analyses to determine how modeling of the muscles and other parameters influence the magnitude of the joint reaction force, as well as compare the magnitude and direction of the joint reaction force in individuals where exercise therapy was successful or failed.

6.1.5 Conclusion

The current study produced novel models for individuals with rotator cuff tears that included subject specific muscle forces, tear characteristics, bony geometry and in-vivo kinematics. The models were also validated with respect to multiple validation criteria including the simulated kinematics, magnitude of the joint reaction force and muscle moment arms and activation. There was excellent agreement between the experimental and simulated kinematics, and muscle moment arms, muscle activations and joint reaction forces met the validation criteria. For any discrepancies, the findings were reasonable based on differences between the current study and previous studies. Utilization of the current subject specific modeling workflow will enable investigation of the effects of a structured exercise therapy program for individuals with rotator cuff tears and potentially determine factors relating to the success or failure of treatment.

7.0 Aim 3: Differences in Joint Stability Between Individuals that Underwent Exercise Only or Exercise Followed by Surgery: A Computational Study

7.1 Individuals with Rotator Cuff Tears Requiring Surgery After Exercise Therapy Have Less Inferiorly Directed Muscle Forces Post-Exercise Therapy

7.1.1 Introduction

The glenohumeral joint heavily relies on the surrounding musculature to stabilize the humeral head on the glenoid. The rotator cuff muscle group is comprised of the supraspinatus, subscapularis, infraspinatus and teres minor with each contributing to stabilization of the glenohumeral joint. Specifically, the rotator cuff muscles coupled with the deltoid comprise the coronal and transverse plane force couples which are vital to maintain concavity compression on the glenoid and was described in detail in Section 1.1.1. In the presence of a rotator cuff tear, the forces crossing the glenohumeral joint may become imbalanced. Generally, individuals with rotator cuff tears will initially be treated with exercise therapy. A major goal of this treatment is to strengthen the intact rotator cuff musculature and balance the forces crossing the glenohumeral joint. However, exercise therapy continues to fail in approximately 25% of individuals (30). One reason for failure may be the inability to properly strengthen and balance the muscle forces crossing the glenohumeral joint that act to center the humeral head on the glenoid.

Given dynamic muscle forces cannot be measured in-vivo, computational models are often employed to estimate muscle forces during varying movements. Estimation of dynamic muscle forces can then be used to quantify the magnitude and direction of the joint reaction force.

Theoretically, if the magnitude of the joint reaction force is decreased and the muscle forces are imbalanced, the humeral head may not be centered on the glenoid. Thus, the objective of the study was to determine the magnitude and direction of the joint reaction force in individuals with symptomatic isolated supraspinatus tears immediately before and after a 12-week personalized exercise therapy program. Individuals that opted for surgery (exercise therapy failed) because exercise therapy did not resolve their symptoms were compared to individuals successfully treated with exercise therapy (exercise therapy successful).

7.1.2 Methods

7.1.2.1 Subjects

Twelve individuals (6 exercise therapy failed, 6 exercise therapy successful, 57.9 ± 10.9 years) provided IRB-approved consent before participation. The primary inclusion criteria included: 1) symptomatic tear isolated to the supraspinatus tendon, 2) partial-(>50% thickness) or full-thickness tear, 3) and age >40.0 years. Eleven individuals had a full- and one had a partial-thickness tear. Individuals underwent a 12-week personalized exercise therapy program. Time to surgery for individuals in the exercise therapy failed group was 1.6 ± 0.9 years. All individuals participated and completed the 12-week exercise therapy program described in detail in Section 4.1.2.3.

7.1.2.2 Glenohumeral Kinematics

Glenohumeral kinematics were measured using a synchronized biplane radiography system immediately pre- and post-exercise therapy during scapular plane abduction as previously described in great detail in Section 6.1.2.3. Briefly, individual-specific humerus and scapula bone models were segmented using MIMICS 20 (Materialise, Leuven, Belgium) from computed tomography images. Three trials of scapular plane abduction were performed on both test days, but the trial in which the individual achieved maximum glenohumeral abduction on each test day was used for all analyses. Digitally reconstructed radiographs of the bone models were created from the computed tomography-based bone models and the known geometry of the biplane radiography system. A semi-automated matching process was used to optimize the correlation between the digitally reconstructed radiographs and the distortion-corrected radiographs for each pair of synchronized images throughout abduction. Glenohumeral joint rotations were quantified with an accuracy of ±0.4mm and ±0.5° (35). Additionally, validation data determined that the simulated kinematics were within ±0.3° for rotations and ±1.1mm for translations in respect to the experimental kinematics when taking into account both pre- and post-exercise therapy.

7.1.2.3 Individual Specific Muscle Parameters

The supraspinatus, infraspinatus, subscapularis, teres minor and middle deltoid geometries were created using MIMICS 20 (Materialise, Leuven, Belgium) and the pre-exercise therapy computed tomography images similar to previous work (189-191). After the geometries were created, they were imported into MeshLab (v2022.02) as STL files and muscle volume was determined for the rotator cuff and middle deltoid muscles using the compute geometric measures operation (192). The maximum isometric force each muscle could produce was based on muscle volume as individualizing muscle forces has been shown to influence predicted joint contact forces and was calculated as previously described (23). For the supraspinatus, infraspinatus and subscapularis, three muscle-tendon units were utilized, whereas one muscle-tendon unit was utilized for both the teres minor and middle deltoid. Specifically, a muscle-tendon unit refers to a line of action for a muscle in the model and this terminology will be used throughout the study.

Three muscle-tendon units were utilized for the supraspinatus to model the anterior, middle and posterior muscle-tendon portions, allowing implementation of tear size and location to further individualize the computational models. Furthermore, three muscle-tendon units were used for the subscapularis and infraspinatus as they are broader muscles with wide attachments. Additionally, different sections of the subscapularis and infraspinatus have been shown to have different function (7, 193). Constructing the models in this manner also allows for consistent implementation of tear characteristics if the tear were to propagate into neighboring tendons. The maximum isometric force each muscle could produce was then evenly distributed among the muscle-tendon units. For example, if the subscapularis was able to produce 600N, the maximum isometric force for each muscle-tendon unit would be 200N. For the supraspinatus, the same method was used, however, an additional step was performed to scale the maximum isometric force for each unit based on the amount of tendon torn.

Isometric muscle strength was also measured pre- and post-exercise therapy by a physical therapist in four joint positions as described in Section 6.1.2.4. To further individualize the model, the ratio of the change in isometric strength was determined (post-exercise therapy strength value divided by pre-exercise therapy strength value) for each joint position. The maximum isometric force for each muscle determined using muscle volume (pre-exercise therapy) was scaled by the ratio change in isometric strength to determine post-exercise therapy values. Since exercise therapy did not include exercises targeting the deltoid, the maximum isometric force was kept constant from pre- to post-exercise therapy. Thus, the current models incorporate individual specific changes in muscle strength following exercise therapy.

The lines of action of the muscle-tendon units were determined using a custom written MATLAB (R2020a, MathWorks, Natick, Massachusetts) code. For muscle-tendon units with three compartments, the width of the origin/insertion was split into three equal sections, and the geometric center of each section was taken as origins or insertions. For muscles with one muscle-tendon unit, the geometric center of the entire origin/insertion was taken as the origin or insertion. The method was proven to be reasonable based on the calculated muscle moment arms determined in Section 6.1.3.

7.1.2.4 Quantifying Tear Characteristics

Ultrasound was used to quantify the anterior-posterior (AP) tear size, tear location and thickness within the supraspinatus tendon as previously described in Section 6.1.2.6. Assessments were performed with a 6-15 MHz linear array transducer (LOGIQE9, General Electric, MA) by a musculoskeletal radiologist. The maximum isometric force for each supraspinatus muscle-tendon unit was then scaled based on the amount of tendon torn. For example, perhaps the maximum isometric force the supraspinatus as a whole could produce was 300N, and the tear characteristics were a full-thickness tear measuring 10mm, tear location of 0mm and superior facet length of 30mm. Given this information, each tendon portion theoretically has a width of 10mm (0→10mm is anterior portion, 10→20mm middle portion, 20→30mm posterior portion) and the tear is 10mm in length and full thickness. Thus, the entire anterior portion is torn and cannot transmit force to the humeral insertion. Since the tear does not extend past the anterior portion, the middle and posterior portions would each have a maximum isometric force of 100N. If the tear was partial-thickness in this hypothetical example, the maximum isometric force the anterior unit could produce would be 100N * (1 - minus the tear thickness ratio).

7.1.2.5 Computational Modeling Workflow and Outcome Parameters

The experimentally measured in-vivo kinematics acted as the input to the drive the models in OpenSim for pre- and post-exercise therapy timepoints, where inverse kinematics was used to minimize the sum of the squared error between the experimental and simulated anatomical landmarks (Figure 7.1). The resulting motion was utilized to determine the muscle forces at each step of the simulation (static optimization, an extension of inverse dynamics) and muscle-tendon units were assumed to be ideal force generators. Thus, force-length and force-velocity relationships were ignored. Previous work has shown this simplified approach is similar to approaches using force-length and force-velocity relationships during gait (194). Furthermore, in the presence of a rotator cuff tear, the relationships may change due to degenerative changes which would introduce additional unknowns and further supports the simplified approach. The objective function minimized the sum of muscle activations squared. Lastly, joint reaction force analysis was utilized to determine the resultant forces at the glenohumeral joint.

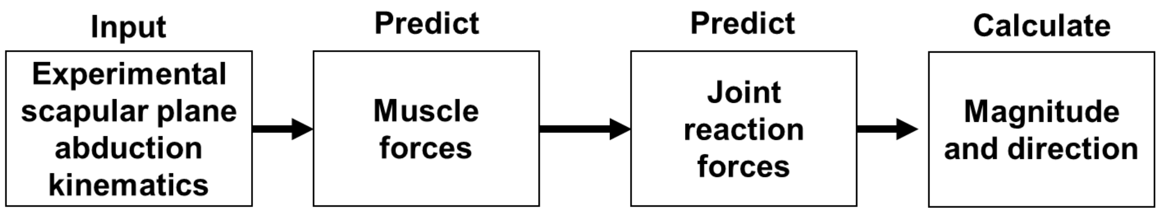

Figure 7.1: Computational modeling workflow to determine the magnitude and direction of the joint reaction force.

Outcome parameters included the magnitude and direction of the glenohumeral joint reaction force during scapular plane abduction. The magnitude of the joint reaction force was normalized to bodyweight (*BW). To describe the direction of the joint reaction force, the elevation and deviation angles were quantified throughout the movement as previously described (20, 214). Briefly, the direction of the joint reaction force in the glenoid based coordinate system was determined, where the elevation angle was quantified in the scapular plane and the deviation angle in the transverse plane (Figure 7.2). For the elevation angle, superiorly directed angles were positive and inferior were negative. For the deviation angle, anteriorly directed angles were positive and posterior were negative.

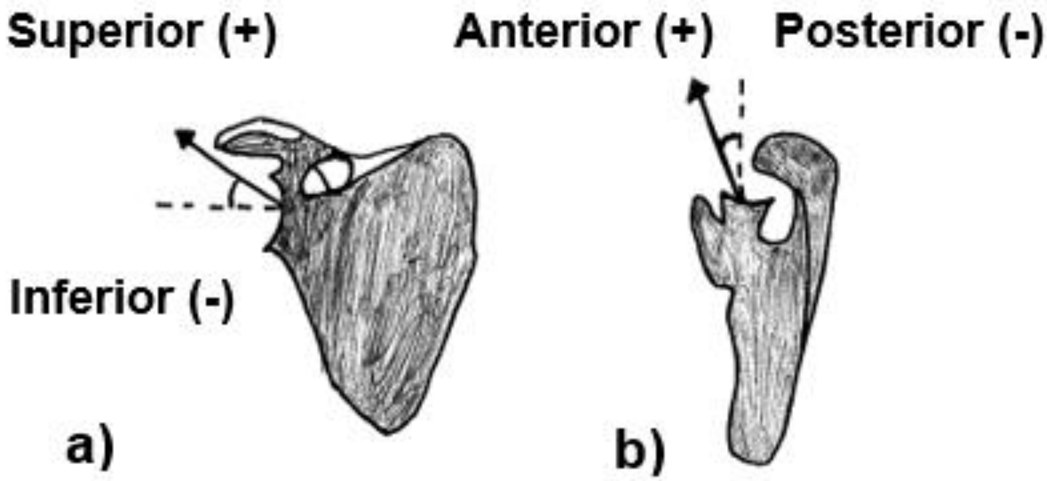

Figure 7.2: Depictions of the direction of the joint reaction force: a) elevation angle in the scapular plane and b) deviation angle in the transverse plane.

7.1.2.6 Sample Size Calculation and Statistical Analysis

The movement on both test days was normalized from initiation of abduction to maximum abduction (0-100%). Statistical parametric mapping was used to compare elevation and deviation angles and the magnitude of the joint reaction force between the exercise therapy failed and successful groups pre- and post-exercise therapy (215). An a priori sample size calculation was performed using internal preliminary data and found 6 subjects were required in each group to detect differences in the direction of the joint reaction force between individuals were exercise therapy failed and was successful (effect size=2.2, α=0.05 and β=0.20). Statistical significance was set at $p < 0.05$.

7.1.3 Results

Throughout scapular plane abduction, no differences in the magnitude of the joint reaction force were observed pre- and post-exercise therapy between the groups ($p>0.05$). For the exercise therapy successful group, the peak magnitude (regardless of point throughout movement) of the joint reaction force for pre- and post-exercise therapy timepoints was 0.64 ± 0.13*BW and 0.67 ± 0.14*BW, respectively. For the exercise therapy failed group, the peak magnitude of the joint reaction force for pre- and post-exercise therapy timepoints was 0.68 ± 0.14*BW and 0.61 ± 0.16*BW, respectively. For the exercise therapy successful group, the magnitude of the joint reaction force increased with abduction to approximately 50% of the movement then decreased pre- and post-exercise therapy (Figure 7.3 and Figure 7.4). For the exercise therapy failed group, the magnitude of the joint reaction force increased with abduction to approximately 70% of the movement then decreased pre-exercise therapy or plateaued post-exercise therapy (Figure 7.3 and Figure 7.4).

The exercise therapy failed group had lower elevation angles between 79-100% of the movement pre-exercise therapy (Figure 7.5, 132.5-142.1° humerothoracic abduction, $p=0.039$). The elevation angle for the exercise therapy failed group was also lower between 58-71% of the movement (Figure 7.6, 108.5-124.8° humerothoracic abduction, $p=0.045$) post-exercise therapy. For both groups, the direction of the joint reaction force pointed superiorly in the scapular plane and increased with increasing abduction. No differences in deviation angles were observed at either timepoint and both groups joint reaction force pointed posteriorly (Figure 7.7 and Figure 7.8, $p>0.05$). The direction of the joint reaction force pointed increasingly posteriorly in the transverse plane with increasing abduction for both groups.

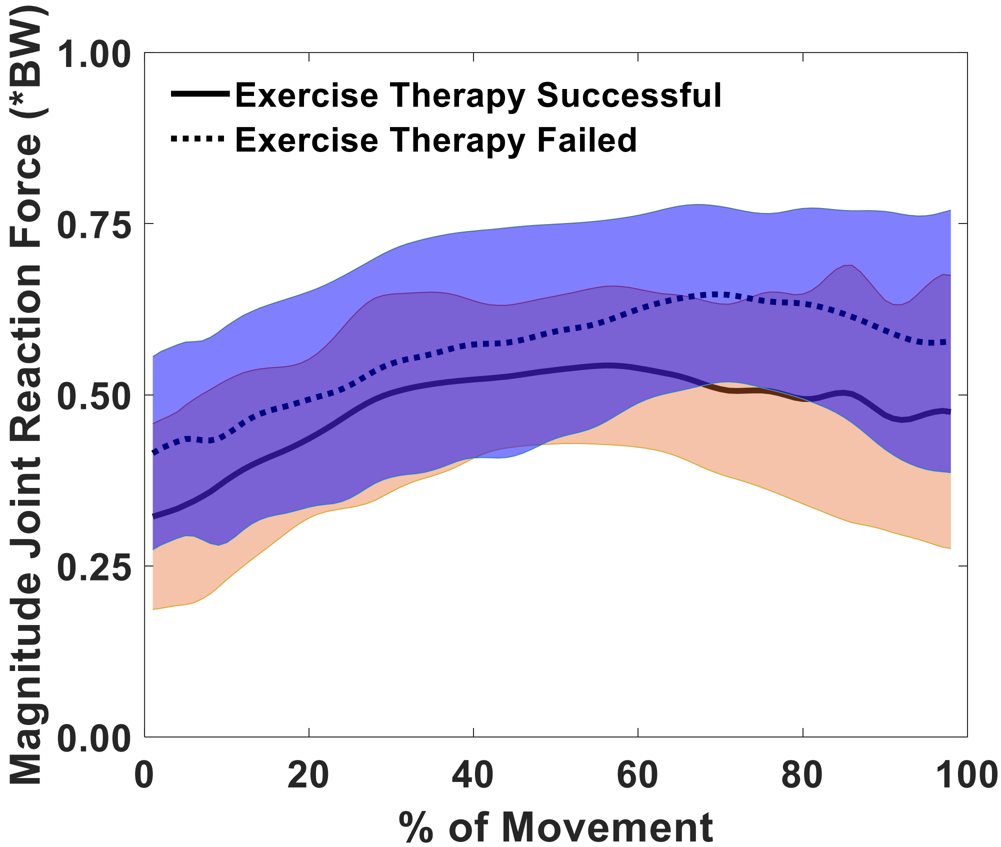

Figure 7.3: Average magnitude of the joint reaction force during scapular plane abduction pre-exercise therapy.

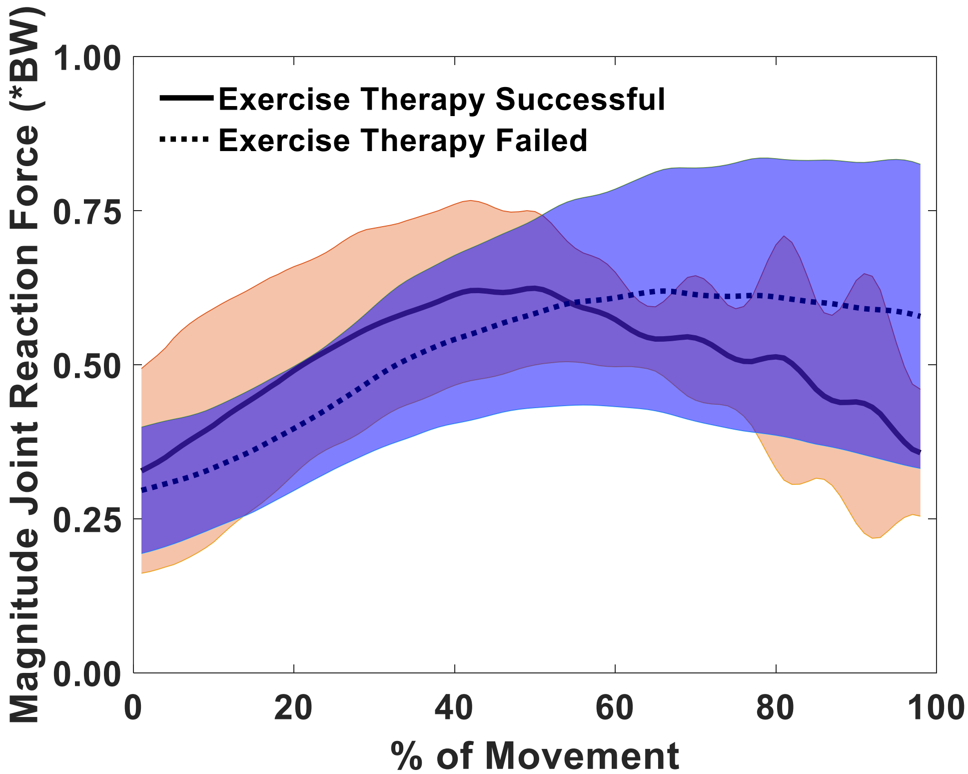

Figure 7.4: Average magnitude of the joint reaction force during scapular plane abduction post-exercise therapy.

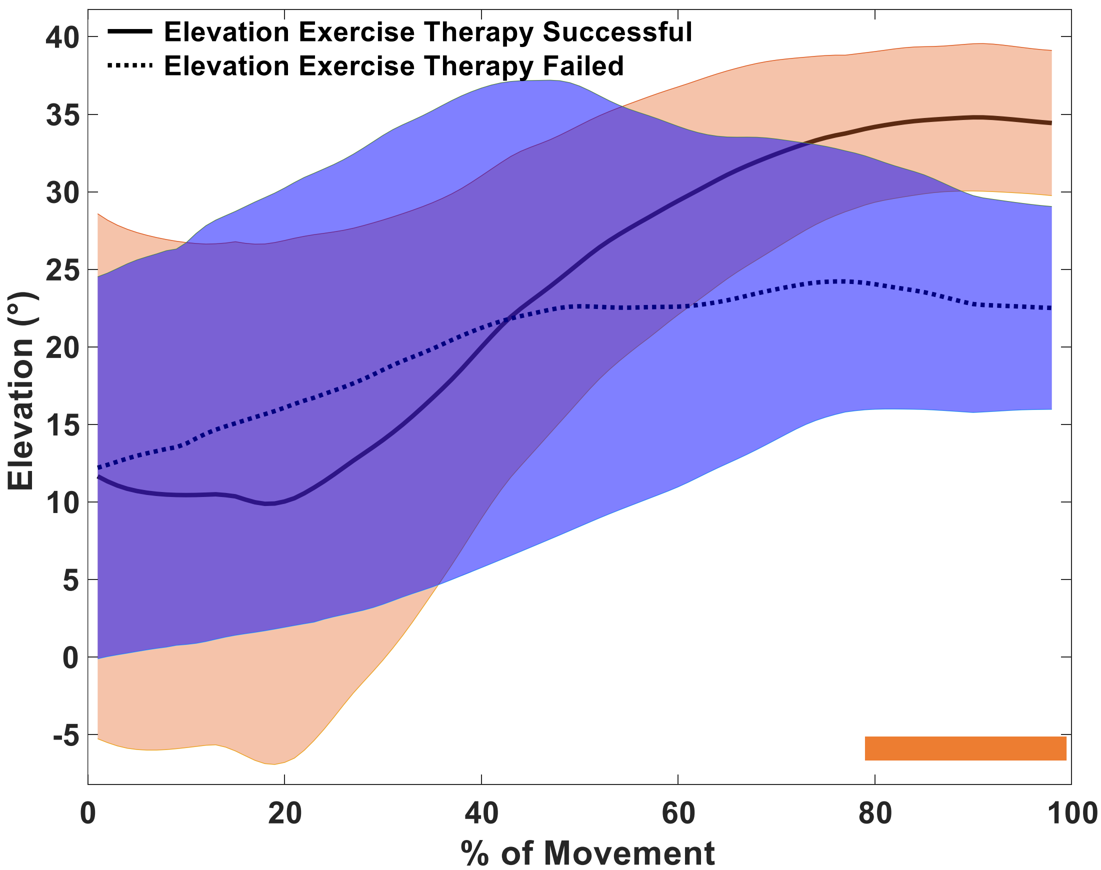

Figure 7.5: Average elevation component of the direction of joint reaction force during scapular plane abduction pre-exercise therapy. The orange bar indicates the portion of the movement where statistically signficant differences occurred.

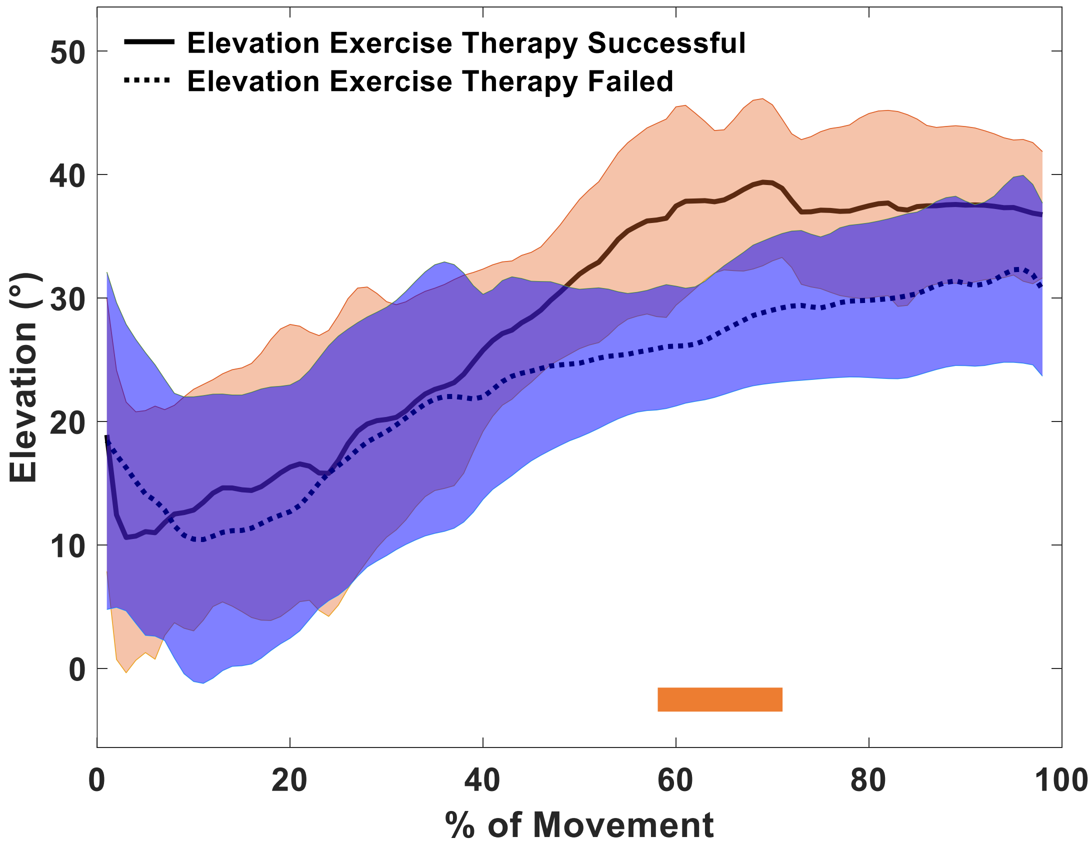

Figure 7.6: Average elevation component of the direction of joint reaction force during scapular plane abduction post-exercise therapy. The orange bar indicates the portion of the movement where statistically signficant differences occurred.

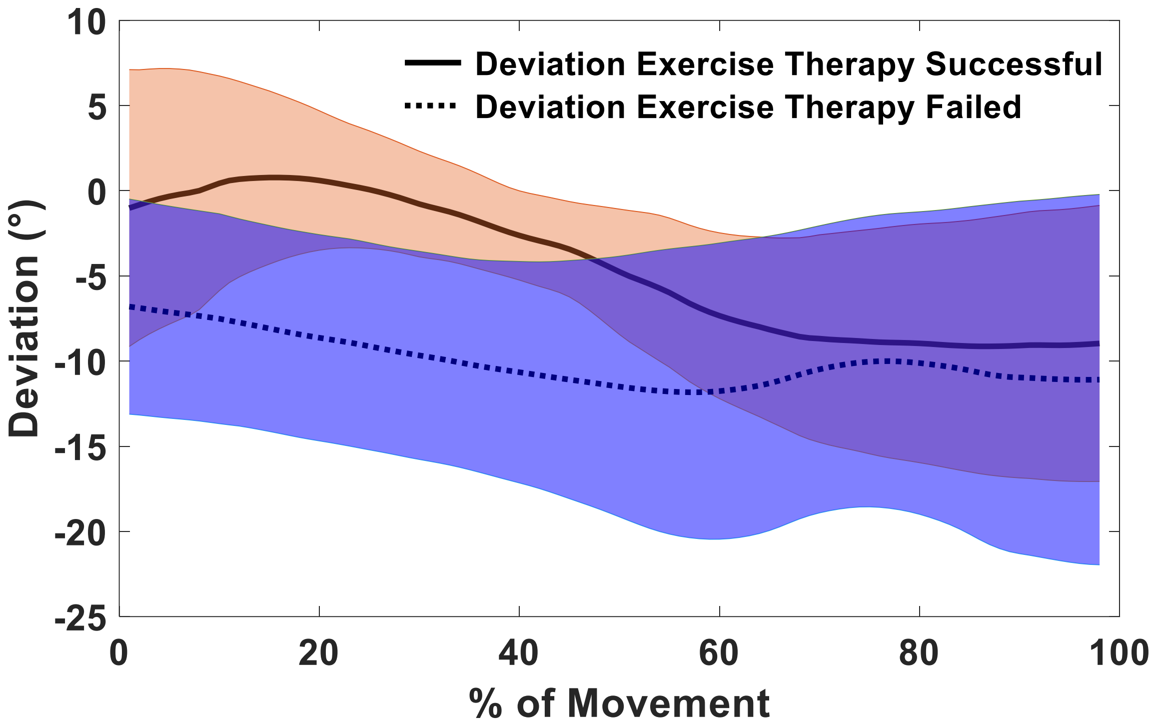

Figure 7.7: Average deviation component of the direction of joint reaction force during scapular plane abduction pre-exercise therapy.

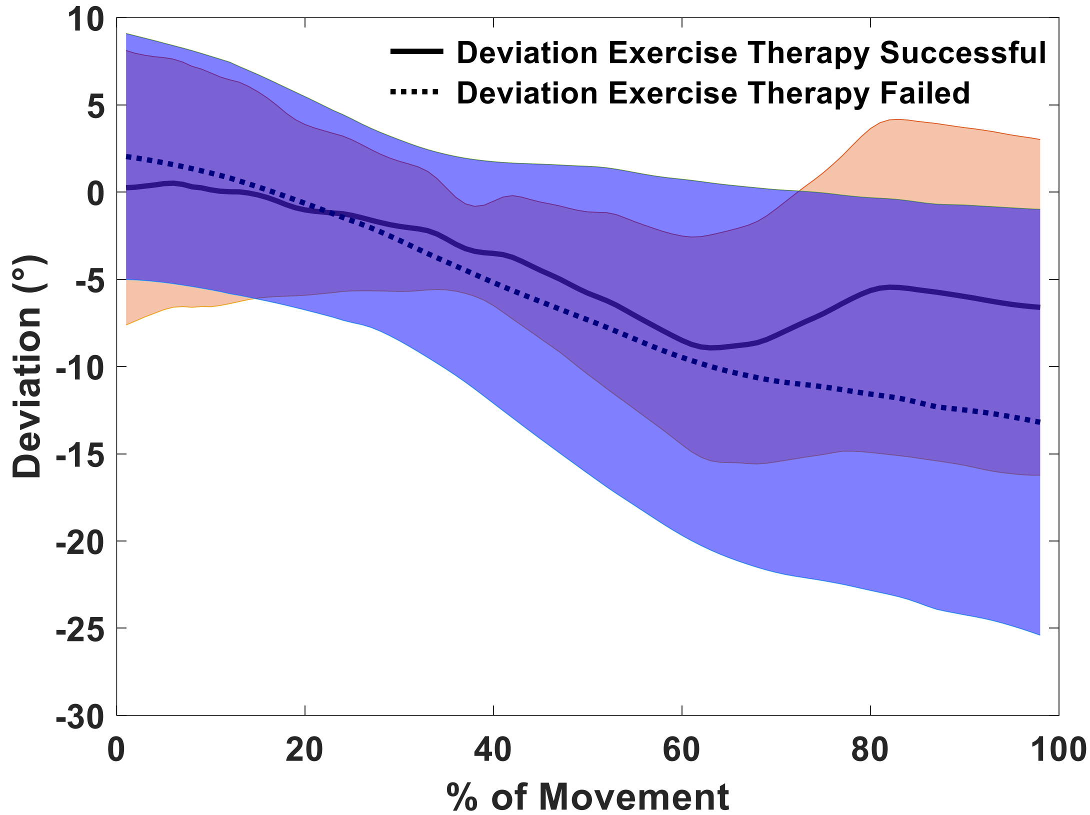

Figure 7.8: Average deviation component of the direction of joint reaction force during scapular plane abduction post-exercise therapy.

7.1.4 Discussion

The main findings of the current study were: 1) the exercise therapy failed group had less superiorly oriented magnitudes of the joint reaction force compared to the exercise therapy successful group pre- and post-exercise therapy and 2) no differences were observed in deviation angles and magnitude of the joint reaction force between the groups. The implications of the first finding are that the exercise therapy successful group have more inferiorly directed muscle forces, resulting in a more superiorly oriented joint reaction force at both pre- and post-exercise therapy. Biomechanically, this implies that the intact rotator cuff of the successful exercise therapy group produced more inferiorly directed forces that could better prevent superior migration of the humeral head. Pre-exercise therapy, the exercise therapy successful group had larger elevation angles between an average of 132.5-142.1° of scapular abduction, demonstrating differences at higher abduction angles. Post-exercise therapy, the exercise only group had larger elevation angles between an average of 108.5-124.8° humerothoracic abduction.

Interestingly, the difference observed post-exercise therapy occurred within the range of motion during which the painful arc is typically observed (216), which is the range where individuals with rotator cuff tears often experience pain potentially due to impingement. This novel finding may be used to identify individuals that will successfully respond to exercise therapy and provide the motivation to modify current treatment algorithms. For example, improvements in the direction of the joint reaction force may be achieved by improving strength of the subscapularis, infraspinatus and teres minor. For individuals with lower elevation angles, additional exercise therapy sessions may be warranted to avoid surgery. An additional implication of the findings is health care cost savings, where subject specific models can be developed into a clinical tool to determine treatment paths. In doing so, unnecessary treatment will be avoided resulting in reduced health care spending.

No differences were observed in the deviation angle between groups at either pre- or post-exercise therapy. The implications of this finding are that when comparing individuals were exercise therapy failed and was successful, the ratio of force between the anterior and posterior rotator cuff was similar. Specifically, the transverse force couple formed by the infraspinatus, teres minor and subscapularis were balanced in a manner that similar function in the transverse plane was observed during scapular plane abduction. The possibility exists that differences may be found if movements involving more glenohumeral internal or external rotation were investigated.

An experimental study using cadavers found contradicting results for the elevation angle but similar results for the deviation angle (20). The joint reaction force for simulated incomplete and complete supraspinatus tears initially pointed inferiorly and became less inferiorly oriented with abduction. The discrepancy is likely influenced by the scapula being rigidly fixed preventing upward rotation that supports the humeral head. Furthermore, when the scapula upwardly rotates, the line of action of the deltoid becomes more medially oriented resulting in less superiorly directed force. In the case of the referenced study, the scapula being rigidly fixed decreases this effect resulting in a more inferiorly directed joint reaction force. For the deviation angle, the referenced experimental study found it remained posteriorly oriented throughout abduction with a relatively constant magnitude of approximately -10° (negative=posterior). Thus, the findings of the current study were similar in regard to the direction of the joint reaction force in the transverse plane.

No differences were found in the magnitude of the joint reaction force between the exercise therapy successful and failed groups. Similar magnitudes of the joint reaction force between the groups indicate the net sum of muscle forces produced are similar and thus generate similar magnitudes. Furthermore, this indicates that both groups develop similar amounts of concavity compression, or ability to pull the humeral head into the glenoid. However, based on the direction of the joint reaction force found in the current study, the amount of force produced by each muscle differs between the groups. Although no differences were found in the magnitude of the joint reaction force, the exercise therapy failed group experienced decreases of 0.07*BW, or 7%.

A limitation of the current study is that no electromyography data were collected to compare to the simulated muscle activation data. However, the muscle activation results were validated in the study reported in Section 6.0. Another limitation of the current study was that each individual may not have remained perfectly in the scapular plane throughout the experimental kinematic testing but were instructed to keep the laser within the target. Similarly, the movement analyzed was from minimum to maximum humerothoracic abduction, however, the range of motion may not be identical across individuals. Furthermore, fatty infiltration and force-length-velocity characteristics of muscles were not accounted for when determining muscle forces. Future sensitivity analyses will be conducted to determine how sensitive the models are to kinematic inputs, muscle origins, insertions and modeling technique and the inclusion of fatty infiltration when scaling muscle forces based on muscle volume.

7.1.5 Conclusion

The current study produced novel models for individuals with rotator cuff tears that included subject specific muscle forces, tear characteristics and accurate in-vivo kinematics. The models were able to distinguish differences in joint function between individuals that failed exercise therapy and those that were successfully treated with exercise therapy alone. Future directions will include determining if individuals with decreased elevation angles respond to additional exercise therapy sessions to improve joint function, as well as various sensitivity analyses. An example of a sensitivity analysis that will be performed is determining how changes in the chosen origins and insertions of each simulated muscle influence the magnitude and direction of the joint reaction force.

8.0 Discussion

8.1 Interrelation of Findings

Together, the three specific aims of the current dissertation investigated the clinical presentation of individuals with symptomatic rotator cuff tears, changes in joint function, patient reported outcomes and tear size following an individualized exercise therapy program and factors that distinguish individuals successfully and unsuccessfully treated with exercise therapy. Aim 1 determined that individuals with symptomatic rotator cuff tears isolated to the supraspinatus tendon present with limitations in shoulder motion and rotator cuff muscle strength. However, the limitations were not associated with abnormal glenohumeral kinematics or patient reported outcomes prior to participating in a 12-week individualized exercise therapy program. Thus, Aim 1 set the stage to evaluate changes in joint function, patient reported outcomes and tear size following an exercise therapy program and determine if limitations in range of motion and strength were addressed.

After characterizing the cohort and determining limitations in function, Aim 2 evaluated changes in multiple variables following a 12-week personalized exercise therapy program. Following exercise therapy, improvements in isometric strength and passive glenohumeral range of motion occurred which were limited in the cohort prior to exercise therapy. Improvements in patient reported outcomes and in-vivo glenohumeral kinematics were observed without increases in rotator cuff tear size. No increases in tear size demonstrate that the risk of propagation following an exercise therapy program was minimal. This finding is novel and provides important information to clinicians when determining treatment plans.

Furthermore, improvements in glenohumeral kinematics and joint stability were observed when reaching the hand behind the back, a novel movement to assess function in individuals with rotator cuff tears. Improvements in joint function, specifically maximum glenohumeral internal rotation and contact path length, were related to patient reported outcomes providing new targetable factors for treatment that may result in improved patient reported pain and function. Arguably, the most important finding was that 92.7% of individuals successfully completed the exercise therapy program. In combination, Aims 1 and 2 characterized functional limitations in the investigated cohort and evaluated changes in joint function, patient reported outcomes, and tear size following exercise therapy in individuals with rotator cuff tears.

A key piece of information missing are the factors related to the failure or success of exercise therapy. Currently, the only factor shown to be related to the failure of exercise therapy is an individual's perception of the effectiveness of exercise therapy (34). Aim 3 directly addresses this important topic using subject specific computational models and comparing between individuals who experienced successful and unsuccessful outcomes following exercise therapy. The validated computational models were utilized to compare joint stability between those that were successfully treated with exercise therapy and those that were unsuccessfully treated (elected to undergo surgery). Individuals successfully treated with exercise therapy had more inferiorly directed muscle forces which may prevent abnormal joint function. Thus, the developed glenohumeral joint models could potentially be utilized to modify treatment modalities based on an individual's joint function. Perhaps, individuals with less inferiorly oriented muscle forces should undergo additional treatment sessions that emphasize improvement of the strength of the subscapularis, infraspinatus and teres minor.

Therefore, in combination, the three Aims of the current dissertation characterized a unique cohort of individuals with rotator cuff tears, evaluated changes in joint function and clinical factors following exercise therapy and determined new targetable factors that can be used to improve current treatment modalities and potentially clinical outcomes. The combined findings provide clinicians with crucial information that may help them make more informed decisions when treating individuals with rotator cuff tears. For example, many believe that immediate surgery is beneficial to prevent the tear from propagating leading to more difficult surgical procedures. However, findings from the current dissertation provide evidence otherwise, informing clinicians that the risk of propagation is minimal. Furthermore, the ability to distinguish who will or will not be successfully treated with exercise therapy will reduce economic burden and optimize treatment algorithms on an individual basis (Figure 8.1).

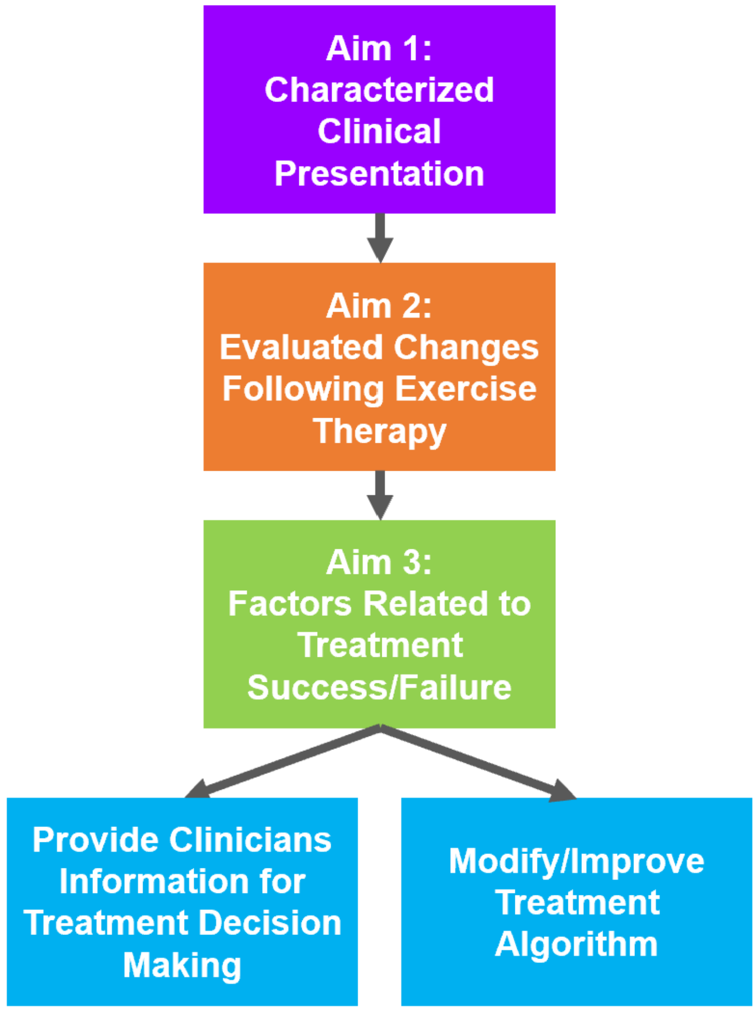

Figure 8.1: Interrelation and implications of findings from the aims.

8.2 Future Directions

The current dissertation developed a well-rounded understanding of changes in important functional and clinical parameters following exercise therapy for individuals with rotator cuff tears. Furthermore, targetable biomechanical factors were identified that may improve future treatment algorithms and distinguish individuals that will or will not be successfully treated with exercise therapy. To continue improving exercise therapy for the initial treatment of rotator cuff tears, future work is required to address important research questions that remain.

For Aim 1, individuals with symptomatic rotator cuff tears isolated to the supraspinatus tendon were characterized with respect to glenohumeral kinematics, isometric muscle strength and various other parameters. In contrast to previous hypotheses in the literature, the current work found no relationships between the limitations observed and glenohumeral kinematics. The implication of this finding was that individuals with the specified pathology maintain reasonable glenohumeral joint function. However, the glenohumeral kinematics used for analyses were only during scapular plane abduction and included only the end range of motion. Future work should perform similar analyses during more provocative movements that may discern abnormal kinematics. For example, the behind the back movement in Aim 3 could be used to determine if glenohumeral joint function is related to patient reported outcomes pre-exercise therapy. Another movement that would be useful for evaluating the function of the intact rotator cuff and glenohumeral joint would be internal-external rotation with the arm abducted. Relationships between glenohumeral kinematics during this movement and isometric strength may elucidate additional factors to be targeted during exercise therapy.

Aim 2 involved evaluating changes in joint function, tear size and patient reported outcomes, from immediately before to immediately after the 12-week exercise therapy program. The findings from Aim 2 demonstrated improvements in joint function (range of motion, strength, glenohumeral kinematics) and patient reported outcomes without increases in tear size. However, important research questions remain regarding the long-term maintenance of an exercise therapy program for treatment of rotator cuff tears. Future work should be done to determine if the improvements observed immediately following exercise therapy are maintained for longer periods of time. The findings of such a study would answer crucial questions such as: 1) Is a 12-week individualized exercise therapy program sufficient to maintain long-term improvements in joint function? 2) Does tear size change long-term following exercise therapy? 3) If improvements were not maintained, is consistent at home exercises sufficient to maintain improvements, or should individuals return for another 12-weeks of exercise therapy? The questions just portrayed are only few of the many important research questions that could be answered with the proposed future work.

Novel subject specific computational models were validated and utilized to investigate joint stability in individuals with symptomatic rotator cuff tears in Aim 3. The models were able to distinguish differences in joint stability during scapular plane abduction between individuals where exercise therapy was successful and failed. Although the findings provide motivation and rationale to modify treatment algorithms, additional work can be done. Future studies will utilize the workflow in Aim 3 to create additional subject specific models to increase the sample size used in the analyses. By doing so, a potential threshold could be created where individuals that fall below a specified value for the elevation angle should receive more than the traditional 12-weeks of exercise therapy or more focus placed on improving isometric strength of the intact rotator cuff muscles. Alternatively, maybe the individual should undergo surgery sooner rather than later. More provocative movements such as reaching the hand behind the back will also be simulated as this may provide additional information on differences between individuals that failed and were successful in exercise therapy. Due to the increased complexity of the reaching behind the back movement, it would be hypothesized that differences would be observed in the magnitude and direction of the joint reaction force.

Then, a new cohort of individuals with symptomatic rotator cuff tears isolated to the supraspinatus tendon could be recruited and the modeling workflow would be used to quantify joint stability of each individual prior to exercise therapy. Based on the outputs, the individuals would be treated accordingly (i.e. more exercise therapy sessions if below threshold) and analyses would be conducted to determine if the alteration to the treatment algorithm improved overall outcomes. An additional subgroup could comprise of individuals that fell beneath the threshold, but still only undergo 12-weeks of exercise therapy to determine if falling below the established threshold predicts failure of exercise therapy. Furthermore, electromyography data could be collected synchronously with the in-vivo glenohumeral kinematics to provide additional validation of the modeling workflow.

Overall, future work applicable to all the Aims would be comparing the findings to healthy individuals with no pathology of the rotator cuff. For Aim 1, comparisons to healthy controls would provide information on specific areas that need to be targeted during exercise therapy. For Aim 2, comparison to healthy controls would allow conclusions to be made regarding the capability of exercise therapy to return glenohumeral joint function to “normal”. Lastly, subject specific computational models could be constructed for healthy controls allowing further comparisons to be made with respect to joint stability and determine “normal” baseline values.

8.3 Summary

Rotator cuff tears remain a significant clinical problem with high prevalence in older individuals. The injury commonly results in the inability to complete activities of daily living especially due to discomfort and pain. Since rotator cuff tears have such a negative impact, determining effective and efficient treatment strategies is critical. The findings of this dissertation included improvements in joint function and clinical parameters without increases in tear size following a 12-week personalized exercise therapy program and determined potential avenues to further improve treatment algorithms.

The major take-home message from Aim 1 was that individuals with symptomatic rotator cuff tears isolated to the supraspinatus tendon presented with limitations in passive range of motion and isometric muscle strength. However, these limitations were not associated with altered glenohumeral kinematics or patient report outcomes. Therefore, individuals with similar characteristics are likely good candidates for exercise therapy to improve function and alleviate symptoms. The findings contribute to the current literature by providing information to clinicians on various variables that influence their initial treatment decision making. Specifically, given there are no serious abnormalities in glenohumeral joint function, exercise therapy may be a more appropriate initial treatment option given it is less invasive.

The key findings from Aim 2 Section 4.0 was that improvements in glenohumeral joint function (in-vivo glenohumeral joint kinematics during scapular plane abduction, muscle strength and passive range of motion) and patient reported outcomes without increasing rotator cuff tear size occurred following a 12-week individualized exercise therapy program. Additionally, 92.7% of individuals successfully completed the entire program (with only 2 individuals electing for surgery, 1 individual receiving an injection, 5 were lost to follow-up/withdrew). No increases in rotator cuff tear size have significant clinical implications as the risk of tear propagation (which would make surgery more difficult) following exercise therapy was minimal. Thus, a 12-week personalized exercise therapy program is a viable initial treatment option for individuals with rotator cuff tears to improve function and alleviate symptoms with low risk of tear propagation.

The major finding from Aim 2 Section 5.0 was that a reaching behind the back movement was useful to assess associations between glenohumeral joint function and patient reported outcomes in individuals with rotator cuff tears. The movement also identified underlying mechanism associated with patient reported outcomes. Specifically, exercise therapy improved glenohumeral internal rotation to similar levels of healthy individuals and improved joint stability, where both improvements were associated with improved Western Ontario Rotator Cuff Index Scores. The unique findings of this portion of the dissertation provide additional information to clinicians and targetable factors during treatment.

The final Aim was also split into two sections (6.0 and 7.0) where Section 6.0 went into extensive detail regarding the construction and validation of subject specific models for individuals with rotator cuff tears. Section 7.0 then performed a comparative analysis on joint stability between individuals successfully and unsuccessfully treated with exercise therapy. The major take-home message of Aim 3 Section 6.0 was that novel subject specific models for individuals with rotator cuff tears were constructed and validated with respect to previous literature. Thus, the novel models can be used to quantify and estimate parameters that cannot be measured in-vivo such as joint reaction forces (can be measured in-vivo with instrumented implants, but there is no clinical indication to do this for the cohort study) and muscle forces.

The findings from Aim 3 Section 7.0 have important implications on how individuals with rotator cuff tears may be initially treated in the future. The major finding from this portion of the dissertation was that individuals successfully treated with exercise therapy had more superiorly oriented joint reaction forces during scapular plane abduction. This implies that individuals successfully treated with exercise therapy had more inferiorly oriented muscle forces, which may prevent superior migration of the humeral head. The implications of this finding are for the modification of exercise therapy protocols and identification of individuals that may be at risk of failing exercise therapy. After individuals are identified as at risk using subject specific models, more focus may be placed on strengthening exercises or they may undergo additional treatment sessions.

Overall, individuals with symptomatic rotator cuff tears isolated to the supraspinatus tendon appear to present with limitations in joint function that can be addressed by individualized exercise therapy programs. Exercise therapy led to improvements in joint function during various movements and has little risk of worsening symptoms and treated most individuals effectively. Utilization of the experimental data then led to novel computational models that can be used in future work to distinguish individuals that will or will not be successfully treated with exercise therapy.

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