An Analysis of Safe Range of Motion after Rotator Cuff Tear Repair using Musculoskeletal Modeling

Team Members

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Background

Rotator cuff is a group of four muscles (supraspinatus, infraspinatus, teres minor, subscapularis) that provides strength and stability for the shoulder. Rotator cuff tear is a common cause of pain and disability among adults. There are more than 250,000 rotator cuff repair procedures performed in the United States every year. Full rehabilitation from the procedure typically takes 6 months until return to a full range of activities. According to Millet et al, in the immediately postoperative period (0-6 weeks post-op), the major goal of rehabilitation is to protect integrity of repair while prevent muscular inhibition [1]. This goal is achieved by a combination of immobilization by slings and passive range of motion (PROM) exercises including shoulder flexion, internal rotation, external rotation, abduction and certain movements that combines the basic degree of freedoms. Patients start active range of motion (AROM) exercises after they recover their pre-operative passive range of motion. AROM exercises usually starts after 6 weeks post-op and last for roughly 6 weeks until patients start to strengthen the muscles. Post-operative rehabilitation plays an important role in the successful recovery from rotator cuff tears. In spite of its importance, rehabilitation protocols are mostly based on clinical experience without biomechanical reasoning to backup the choice of exercises. As a result, there is tremendous variability in postoperative rehabilitation protocols in terms of length of immobilization, early safe range of motion, and the timing for moving on to more rigorous exercises[2]. A biomechanical study of the exercises will make a significant contribution to developing a evidence-based rehabilitation protocol.

Goals

Injury to unhealed tendon directly relates to excessively loading of the tendon during rehabilitation, which provides an opportunity of evaluating rehabilitation protocols by musculoskeletal modeling. Compared to cadaveric study, simulation based study covers a wide range of poses more efficiently and allows the study of active muscle force. Compared to EMG study using healthy volunteers, simulation is capable of capturing the property change of the muscles due to the repair. In this study, musculoskeletal modeling is used to study muscle force during PROM and AROM exercises. The goal is to inform a safe space for early passive range of motion and to inform a safe progression of exercises. Among four rotator cuff muscles, supraspinatus is the most commonly injured one. This study will focus on the rehabilitation after supraspinatus tendon repair.

Methods

A publish model (shown in figure 1) of the upper extremity was modified to study the different shoulder poses [3] [4]. 17 muscles that crosses the shoulder joint were enabled and three degress of freedom were unlocked: shoulder elevation (0-180 degree), shoulder rotation (-90-20 degree, positive angle is internal rotation, negative angle is external rotation), and rotation plane (-90-130 degree, positive angle is in front of the body, negative angle is behind the body). In order to model supraspinatus tendon after surgical repair, the tendon slack length was reduced by 2cm, which is a common tendon retraction seen in patient with a medium size tear [5].
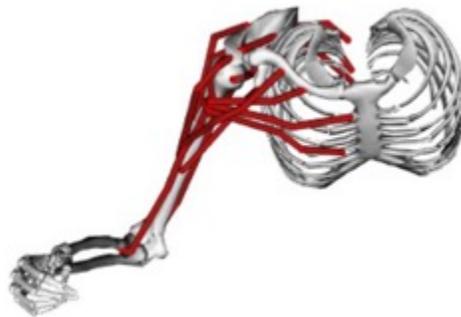

Figure 1: Saul 2015 model

A motion file that contains all possible combination of the 3 DOF in 10 degree increments was created. When studying PROM exercises for phase I of rehabilitation (solid lines in figure 2), the model and motion file were fed to the analyze tool to study the passive muscle force at different poses. When studying AROM exercises for phase II of rehabilitation (dashed lines in figure 2), the model and the motion files were fed to static optimization tool to study muscle activation and muscle force. For the static optimizer, the power of the objective function was set to 10 to achieve min/max criterion, which is an reasonable approximation for upper extremity muscles [6]. Furthermore, the activation distribution between supraspinatus and deltoid roughly matched the result from EMG study [7].
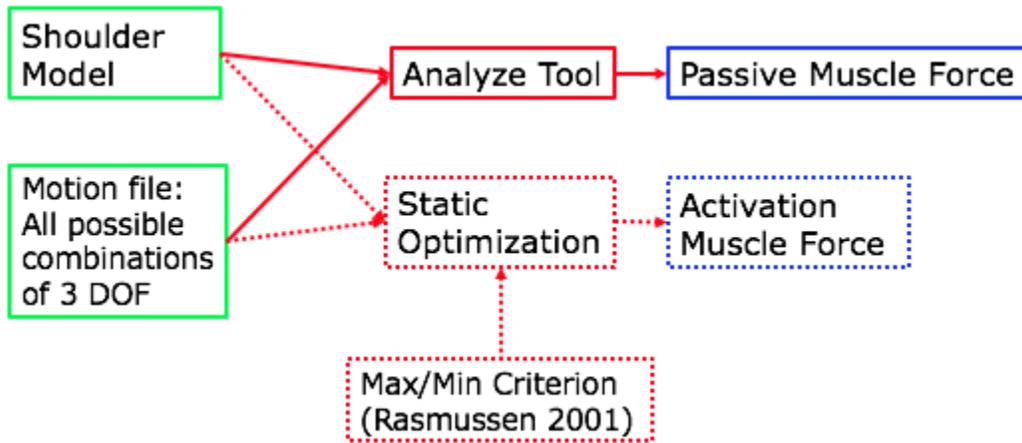
Figure 2: Flow chart for the analysis process

Results

Two commonly used PROM exercises are shoulder elevation and shoulder rotation. In rehabilitation sessions, the patient use the healthy arm to elevate or rotate the injured arm or the therapist holds the patient's arm to elevate or rotate. Figure 3 shows how passive supraspinatus force changes when the patient is doing the flexion exercise from the coronal plane (0 degree elevation plane) to sagittal plane (90 degree elevation plane). The passive force is at the maximum when the arm is not elevated. As the elevation angle increases, the passive force decreases. Doing flexion exercise in which plane does not change the maximum force much but as the arm moves from the coronal plane to sagittal plane, the force decreases slower. A cadaveric study measuring the load in supraspinatus tendon at different elevation angle in coronal plane and sagittal plane showed the same trend [8].
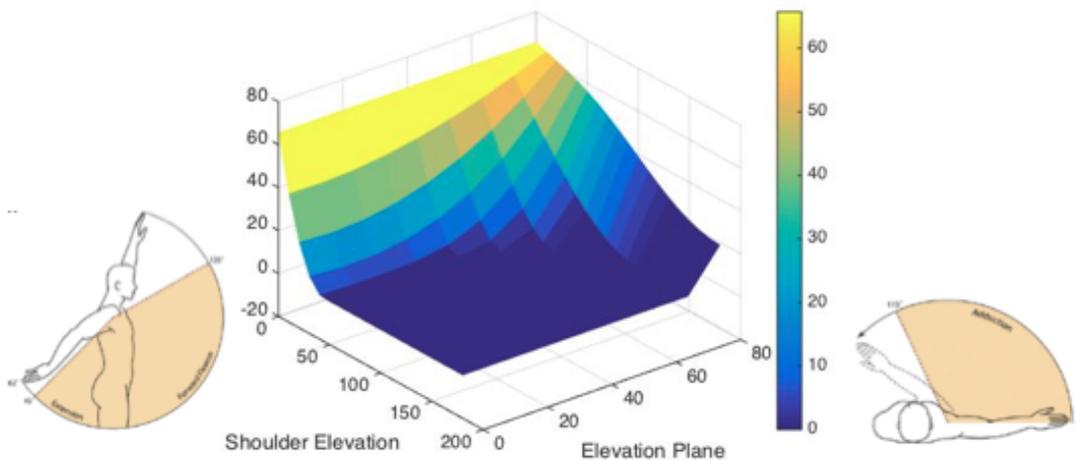

Figure 3: Passive supraspinatus force vs. shoulder elevation and shoulder elevation plane

Figure 4 shows how passive supraspinatus force changes when the patient is doing external rotation exercises with the arm elevated at different angle. The plot shows the maximum force occurs when the arm is maximally internal rotated. As the arm rotates more and more externally, the passive muscle force drops. The cadaveric study also showed external rotation reduces passive muscle force [8]. Doing the exercise with arm elevated reduces the maximum force but does not affect how fast the force reduced as the arm externally rotates.
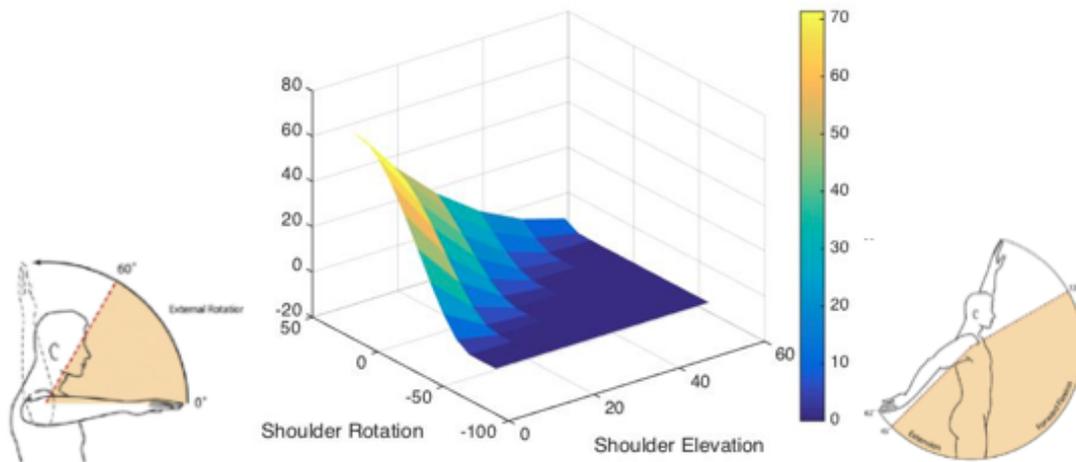
Figure 4: Passive supraspinatus force vs. shoulder elevation and shoulder rotation

With the general trend matched with experimental study, it is reasonable to conclude that this model is capable of producing physiological trends. Figure 5 illustrates what poses is safe or unsafe for early passive range of motion exercise. The criteria for unsafe condition is when passive muscle force exceeds 215N, which is the failure load for the suture anchor [9]. The safe space is defined as the passive muscle force is lower than 2N. While the safe pose depends on all three degrees of freedom, in general, patients should avoid placing the arm over 90 degree or -50 in the elevation plane. The safety of the poses when the arm is in elevation plane between 0 and -50 or between 50 and 90 degree is decided by shoulder elevation. The pose is safer when the arm is more elevated. When the arm is in elevation plane between 0 to 50 degree, any poses with shoulder elevation higher than 40 or external rotation higher than 50 are safe.
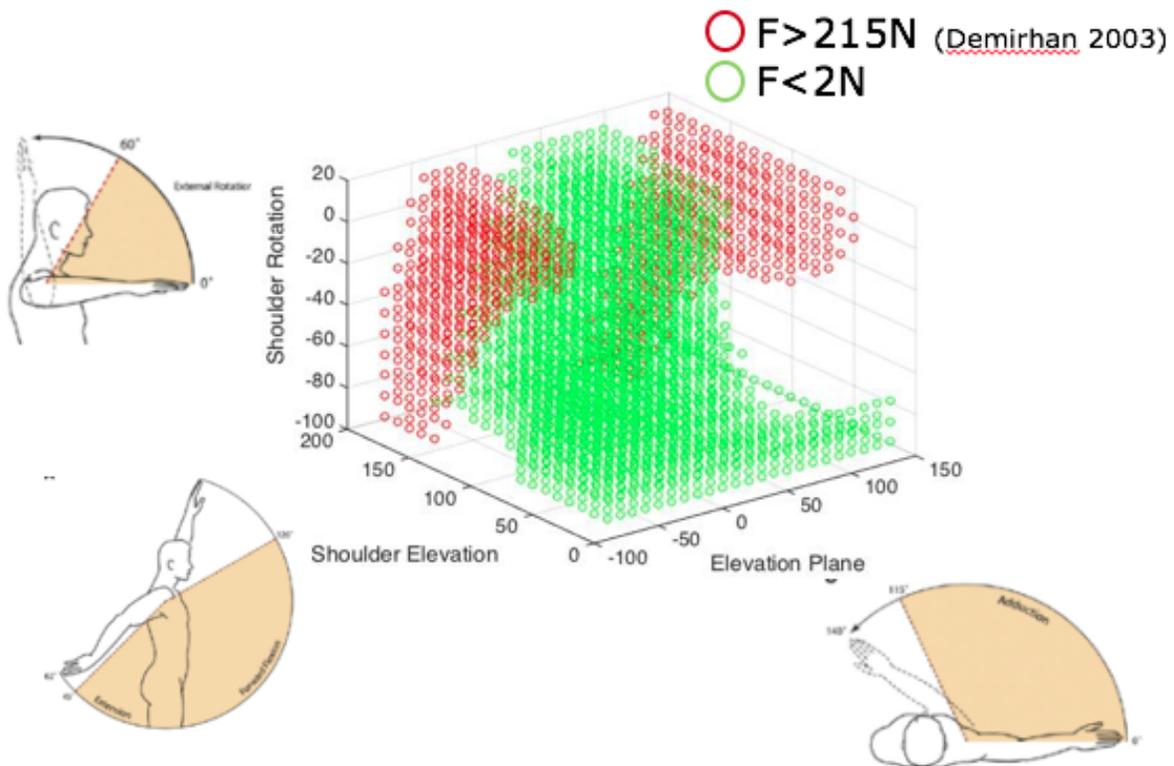

Figure 5: Safe and unsafe spaces for early passive range of motion

Active range of motion exercise starts 6 weeks after the procedure. Shoulder flexion and rotation are still the most commonly used exercises. Sometimes, patients use sticks or pulleys to assist the injured arm. The goal for this stage of exercises is to recover to full range of motion. Figure 6 shows supraspinatus force during shoulder active rotation with the arm elevated at 0, 30, and 90 degrees. The figure shows more active muscle force is needed as the shoulder externally rotates. The muscle force also increases as the arm elevates more. When shoulder is elevated at 90 degree, supraspinatus force drops to 0, which is due to limitations of the model. The limitation of the model will be discussed in discussion section.
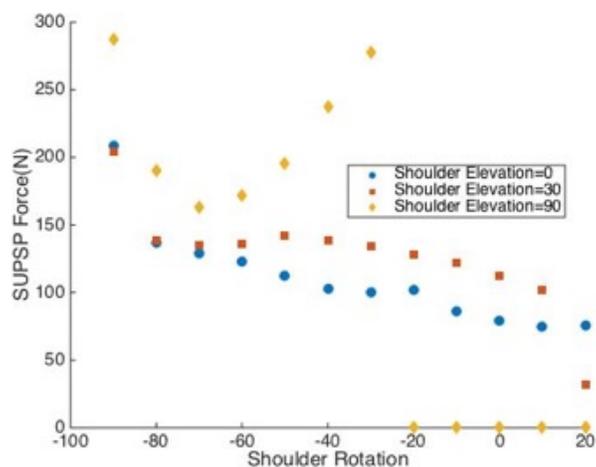
Figure 6: Supraspinatus force during shoulder active rotation

Figure 7 shows supraspinatus force during active shoulder flexion in 40, 60, and 90 degree in the elevation plane. All the curve shows an increasing then decreasing trend. The maximum force occurs at different elevation angle depending on in the plane of elevation. The general trend shows doing elevation closer to the coronal plane causes higher muscle force than doing it in the sagittal plane. For the curve showing flexion in 60 degree elevation plane, muscle force showed discontinuation at 90-110 degree. This discontinuation is not physiological and is caused by limitations of the model, which will be discussed in the next section.
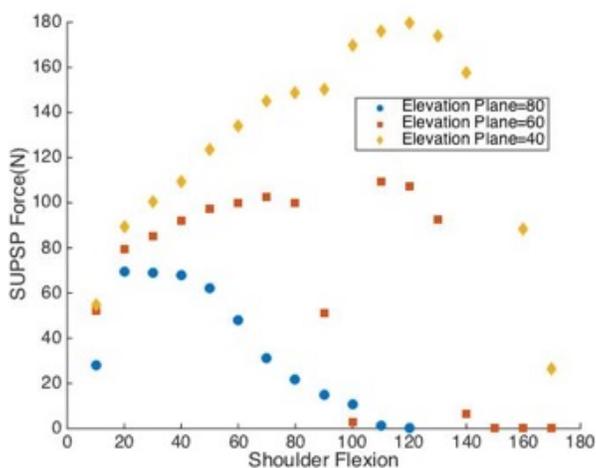
Figure 7: Supraspinatus force during shoulder active elevation

Discussion

The result from analyzing passive range of motion showed encouraging indication for the safety of staring PROM exercises early. Early movement promotes blood flow and prevents muscle tightness for healthy shoulder muscles, which may help the recovery. The result from this study shows certain poses do put the muscle under unsafe load, but there is a large space for safe early PROM exercise. Due to the lack of an evidence-base rehabilitation protocol, some surgeons start unrestricted PROM as early as within 2 week after procedure and some hold off until week 6 or 7 [2]. It is too aggressive to start unrestricted PROM that early; However, in certain degrees of freedom, the safe range of motion is larger than what some surgeons believe. In a evaluation-based rehabilitation protocol, the patients are advice to keep the external rotation angle below 35 degree and flexion angle below 90 degree [1]. It is time to reconsider that advice since both simulation and cadaveric study showed higher external rotation angle and flexion angle reduces muscle passive load. Based on this study, it is safe to elevate the arm higher than 90 degree and rotate the arm pass 35 degree after supraspinatus repair. However, flexion angle below 30 and internal rotation of the shoulder should be avoided in early post-operative period, which indicates the safe pose to wear the sling is about 30 degrees of abduction with 20 degree external rotation.

In the stage of doing active range of motion exercises, the result from this study shows doing the same exercise in different poses varies supraspinatus load. The result shows doing flexion exercise in 40 degree elevation plane doubled the peak muscle load compared with doing it in 80 degree elevation plane. This trend indicates the therapist should clearly describe the proper pose for exercise and ideally the device used for assistance should be set up in a way to reinforce compliance. This trend also provides a safe progression of the exercises. For example, the patient should start flexion exercise in in the sagittal plane. After the patient is able to reach 180 flexion in sagittal plane without pain, he or she can work progressively toward pain free flexion in coronal plane. In this way, the therapist can avoid prematurely starting abduction exercise and the patient can have a sense of his or her rehabilitation progress. Similarly for external rotation, the patient can start from holing the upper arm in 0 elevation and work progressively toward doing with the upper arm elevated in 90 degree.

Before using the result from this study to make evidence-based rehabilitation of supraspinatus tear, several limitations should be taken into account. First, 30% of the poses failed static optimization. Some of the poses at the limit of range of motion failed because they are physiologically impossible; however, most of the failed poses are physiological. For example, static optimization failed for arm flexion higher than 110 degree in sagittal plane, which is obviously achievable. Second, some of the solved poses showed unrealistic activation pattern. As described in the result section, the activation showed discontinuity. In general, most shoulder elevation angle higher than 90 degree causes failed static optimization or produced unrealistic result. Due to these limitations, this study is comparing different exercises qualitatively, not quantitatively. Third, the criteria used for unsafe range is defined as the failure load of the suture anchor. A better definition should be used to prevent tendon re-tear. Furthermore, in clinical practice, the pain is usually used as the indicator of safety. Excessive loading certainly causes pain but other factors should also be considered such as swelling and inflammation. A safe pose may cause pain due to non-mechanical factors.

Future work:

This study shows encouraging preliminary result to provide basis for evidence-based rehabilitation protocol. To move forward, model refinement for reliable active muscle force estimation is necessary. There are three ways to improve the model:

1) Modify the muscle paths: I tested the moment arms of supraspinatus as well as deltoid muscles for some combinations of the degrees of freedom. The moment arms showed some discontinuities. Modifying the muscle paths to provide continuous moment arms should reduce the discontinuity in active muscle forces.

2) Add muscles responsible for elevating the scapula: The most common reason for failing static optimization is the deltoid muscle reaching maximum activation. Since some muscles for elevation the scapula were not in the model (such as serratus and rhomboid muscles), the deltoid muscles in the models are experiencing higher than physiological loads. Add the scapula elevator should prevent the deltoid muscles from maxing out and will improve the accuracy of the model for high shoulder elevation.

3) Improve the joint definitions to eliminate phantom bodies: Phantom bodies are used to define the glenohumeral joint in the model. Those nearly massless bodies may caused some difficulties in finding a solution for static optimization.

This study builds a frame work that can be applied to study other aspects of rotator cuff injury rehabilitation. With a reliable model for static optimization, repeating this study with load to analyze more advanced rehabilitation phases, and repeating this study for injury in other rotator cuff muscles would make great contribution to build evidence-based rehabilitation protocol.

Acknowledgements

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