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Design and Implementation of a Shoulder Simulator

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Honors Capstone Project in Bioengineering

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Abstract: The main objective of this thesis project is to build a shoulder simulator to be able to understand the mechanics of the shoulder, specifically the rotator cuff and deltoid muscles. The shoulder simulator should be able to mimic the important motions of the human shoulder by pulling on tendons of cadaver shoulders and moving the shoulder in various specified motions. In my thesis project, I worked on creating a shoulder simulator that would control the rotator cuff muscles along with the three deltoid muscles. In order to do this, I needed to design and test the shoulder simulator using cadaver shoulders. With the use of a control algorithm which was created prior to my project, the simulator was able to control the cadaver shoulders by pulling on the various tendons. My specific contributions to the project were designing and building the shoulder simulator, dissecting shoulders, testing shoulders in the shoulder simulator and evaluating the shoulder simulator through data analysis.

Contents

Introduction:

Shoulder simulators have been used to study the mechanics of the shoulder. They provide information about the forces and motions of the shoulder. The motions of the shoulder are complex, especially when there is damage done, such as in rotator cuff tears. This is why it is so important to create a shoulder simulator that truly mimics the motions of a shoulder. It can be beneficial to many. One example of how the shoulder simulator can be used is in the testing of shoulder implants. One can implant the cadavers with shoulder implants and then make the shoulder repeatedly move in various motions so that they can see how the implant works. One can also use the shoulder simulator to test various motions and to understand which muscles do what in various motions.

Methods:

Literature Review

Before designing and building the shoulder simulator, it was important to read many papers about the subject. Most of them explained past shoulder simulator projects and explained how the muscles work.

One of the most important papers was done by David Ackland and Marcus Pandy, *Lines of action and stabilizing potential of the shoulder musculature*. In this paper, they looked at the lines of action of 18 major muscles of the shoulder. They have a set of graphs within their paper that showed the various lines of action of those muscles. We used those graphs to figure out how to design our shoulder simulator to have the correct lines of action. More on this design aspect can be found in the Design section.

Moment arms of the muscles crossing the anatomical shoulder, also by Ackland and Pandy, was very helpful. Again, they looked at 18 muscles of the shoulder. This time, however, they studied the moment arms of each muscle. It is important to understand the moment arms of the muscles, because the magnitude of the moment arm affects how much of a moment a muscle can apply for a particular motion. This paper was specifically useful for our research because it helped us to recognize which shoulder muscles are the most active during which motions. In turn, this also helped us to make sure that the muscles we focused on would actually be instrumental in moving the shoulder cadaver in the specified motions.

Shoulder muscle moment arms during horizontal flexion and elevation by Kuechle et. al looked at 10 shoulder muscles of the glenohumeral joint, including the rotator cuff and the three deltoid muscles. The various muscles that were active in those particular motions were explained, so it was easy to gather information on how the muscles should act in our shoulder simulator. This information was useful when we evaluated how our shoulder simulator worked. Without this information, it would have been very difficult to evaluate if our simulator was successful or not.

Another similar paper was by McMahon et. al, *Shoulder muscle forces and tendon excursions during glenohumeral abduction in the scapular plane*. In this paper, they looked at the rotator cuff muscles along with the middle deltoid. In particular, they looked at four different situations or cases: 2:3 ratio of force applied to middle deltoid/supraspinatus, 2:3 force ratio applied to middle deltoid supraspinatus, 3:2 force ratio applied to middle deltoid/supraspinatus, zero force applied to supraspinatus. In doing this, they gathered information about how the rotator cuff muscles function in each of those cases, which are related to different problems or issues in the shoulder. It was found that the supraspinatus and deltoid muscles work together and substitute for each other when either one of them is not working correctly.

Their shoulder simulator setup can be seen in Figure 1, from their paper. Looking at this setup as well as the others gave me some idea of how our simulator should work.

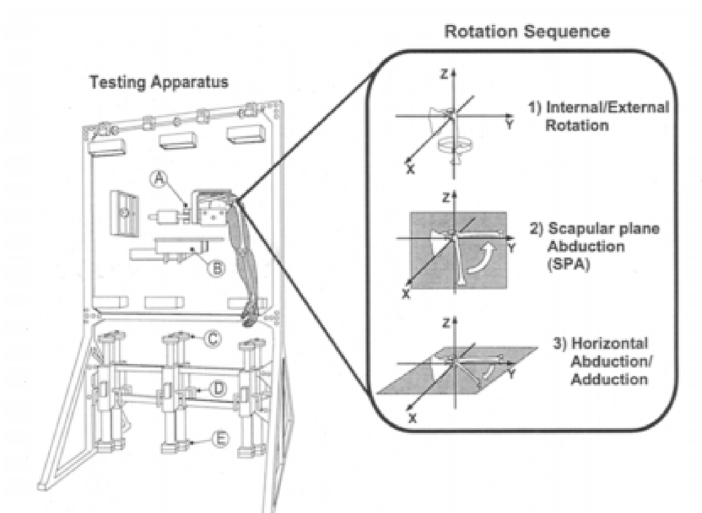

Figure 1 Pittsburgh dynamic shoulder testing apparatus. *A*, Scapular mount; *B*, magnetic tracking device platform; *C*, load cell ($n = 6$); *D*, hydraulic cylinder ($n = 6$); *E*, linear variable differential transducers ($n = 6$). Insert depicts rotation sequence used to describe humeral orientation.

Electromyographic Analysis of the Supraspinatus and Deltoid Muscles during 3 common rehabilitation exercises by Reinold et al was used to figure out which muscles work in different shoulder motions, specifically the "full can", "empty can", and "prone full can" exercises. These correspond to standing elevation, standing elevation with internal rotation and abduction with external rotation, respectively. In this study, they found that the activity of the supraspinatus muscle didn't vary much across the various exercises. However, they found that the activities of the middle deltoid and posterior deltoid varied greatly across the exercises. The middle deltoid was found to have greater activity during the last two exercises. This paper was useful in telling us when the deltoids should be active during abduction, which is one of the motions that we focused on.

Another very useful paper was Lugo, Roberto et. al, *Shoulder Biomechanics*. In this paper, they summarized the different actions of the muscles that we are focusing on for our shoulder simulator (*see Table 1*).

Table 1
The rotator cuff muscles and description of function

Rotator cuff muscle	Description	Action
Supraspinatus	Circumpennate muscle. Average width at midportion of tendinous insertion is 14.7 mm. Mean area of insertion is 1.55 cm^2	Initializes humeral abduction to 90°
		Deficiency can be compensated for by the remaining rotator cuff muscles
Infraspinatus	Circumpennate muscle. Mean area of infraspinatus insertion is 1.76 cm^2	Resists posterior and superior translation Generates 60% of external rotation force
Teres minor	Circumpennate muscle	Resists posterior and superior translation Generates 45% of the external rotation force
Subscapularis	Multicircumpennate muscle	Contributes to the floor of the bicipital sheath Resists anterior and inferior translation Strong internal rotator

In this paper, they also talked about how the rotator cuff muscles work together to create a "fine control muscle system." This paper gave great detail on how the shoulder muscles work to create the motions.

Experimental investigation of reaction forces at the glenohumeral joint during active abduction by Apreleva, et al, provided me with information about how the muscles work during abduction. In this paper, they found that the magnitude of the reaction forces changed with the different ratio of forces of the deltoid and supraspinatus muscles. Figure 1A, from their paper, shows their shoulder simulator design.

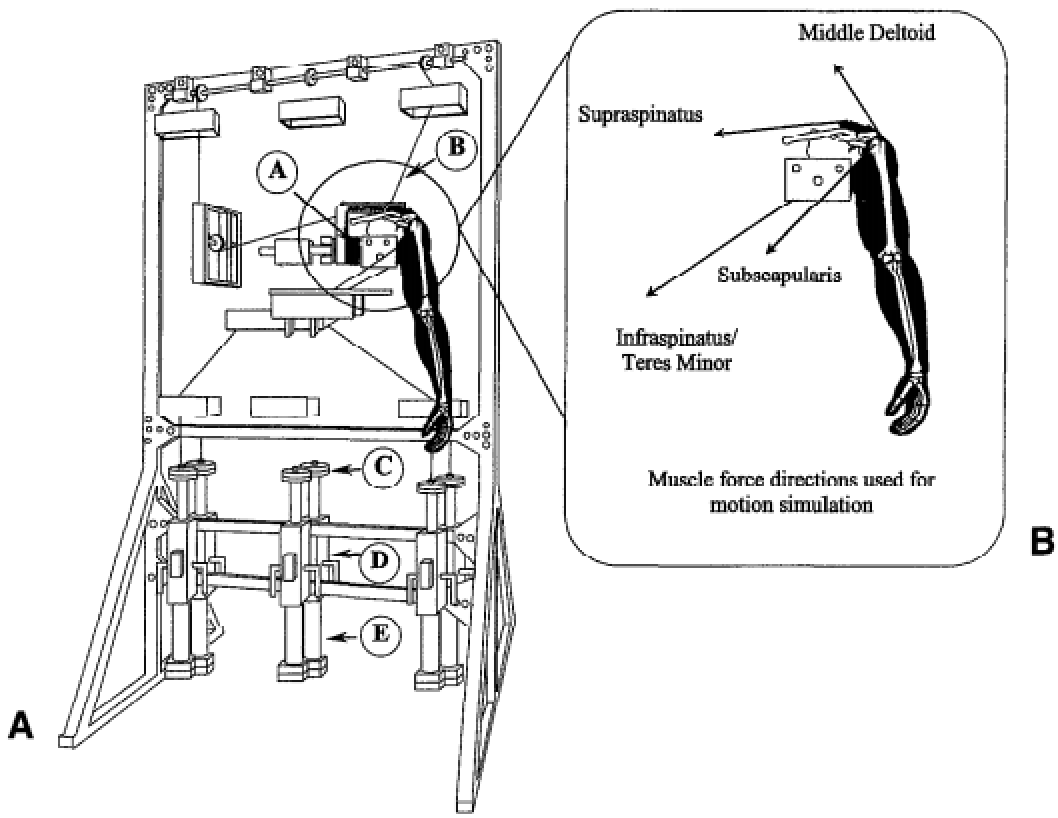

Figure 1 **A**, Pittsburgh DSTA. *A*, UFS attached to scapular mount; *B*, cable-pulley system; *C*, load cell; *D*, hydraulic cylinder; *E*, linear variable differential transducer. **B**, Muscle force directions used for motion simulation. Infraspinatus/teres minor, 51°; subscapularis, 58°; supraspinatus, 8°; deltoid, 5 mm dorsal to anterolateral corner of acromion.

Another shoulder simulator design was found in Hughes, Richard et. al, Comparison of two methods for computing abduction moment arms of the rotator cuff, as seen in Figure 1.

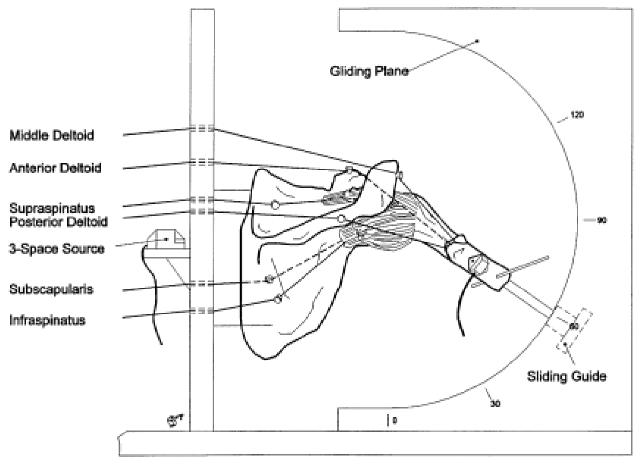

Fig. 1. Experimental setup.

As you will see in the design section of this paper, our design for the shoulder simulator we created had some similar aspects to each of the shoulder simulators that were found in these papers. For example, our setup for the holes for the cables for the various muscles was similar to that of the Hughes et. al paper. However, our simulator is different from all of the previously shown simulators. The pictures that are included in this paper were majorly included in this paper to help the reader achieve a better understanding of how shoulder simulators work and function.

Another paper that was used to find out how the muscles work together to produce motions was *Muscle Activity and Coordination in the Normal Shoulder* by Kronberg et. al. They used EMG activity to describe the activity of the muscles during external rotation, internal rotation, shoulder flexion and shoulder extension. They found that the infraspinatus and subscapularis acted as stabilizers during flexion and the subscapularis acted as a stabilizer during external rotation. The subscapularis also worked with the supraspinatus during extension. They also figured out which muscles are movers during each motion. Movers are muscles that are instrumental in moving the shoulder in specific motions, so knowing a muscle is a mover during a specified motion tells us that it should be very active during that motion. This information helped us evaluate the simulator after testing.

A paper I used to understand the anatomy of the shoulder was *Functional Anatomy of the Shoulder* by Terry, Glenn et. al. The authors talked about all the different parts of the shoulder, including the scapula and clavicle. This paper provided me with basic anatomy so that I was able to successfully dissect shoulder cadavers.

A summary of my findings from the literature on which muscles should do what during which motion can be found in Table 1.

Table 1. Muscle Activities During Motions Based on Literature

Motion	Movers	Stabilizers
Abduction	Anterior/Middle Deltoid, Supraspinatus	Infraspinatus, Subscapularis
Adduction	Posterior Deltoid	
Flexion	Infraspinatus, supraspinatus	Subscapularis
Extension	Subscapularis	None

Previous Work

It is important to note that there has been much previous work done on the simulator. Michael Shorofsky worked on the shoulder simulator from 2008 to 2009 for an SU independent study project and senior design thesis. For his project, he worked on defining which muscles to use as well as the preliminary setup of fixtures.

Brian Santacrose worked on the shoulder simulator in 2010 as a SUNY Upstate medical student. He worked on anatomy and dissection. Michael McGrattan, who worked on the shoulder simulator in 2011 as a SUNY Upstate medical student, worked on anatomy, potting and making the fixtures.

Lastly, Levi Sutton worked on the shoulder simulator from 2008 to 2010. He worked in the lab and design and make a number of fixtures for the simulator.

Design

In designing the shoulder simulator, we looked at previous shoulder simulators from other research groups, as seen in the Literature Review section.

Control Theory/Program

For this project, we used a previously used program written for a wrist simulato (reference to Werner et al, Wrist Joint Motion Simulator. J Orthopaedic Research 1996:14:639-646), slightly modifying it to fit the shoulder simulator. The important things that the program allowed us to do were:

1) adjust the zero levels of each tendon's load cell prior to testing the shoulders in the shoulder simulator.

2) Look at the general terminal emulator

This gives the position of the sensor in 3-dimensional space and is used to know where the shoulder is located.

3) Edit the control parameters file

Selecting this option brings up a header file, in which the user can change parameters used in the shoulder simulator testing, such as center of rotation and the desired range of shoulder motion. During testing, we also changed the antagonist and agonist feedback gains to make the simulator work well.

4) extend/retract the cylinders

Extending the cylinders allowed us to "release" the tension in the cables, since the hydraulic cylinders would move all the way out. It was important NOT to retract the

cylinders if the tendons were attached, because retracting them could ultimately pull the tendons off the shoulder cadaver.

5) run mount

This part of the program allows the user to turn on the hydraulic system so that each cylinder is applying the same amount of force on each tendon in the shoulder cadaver. This was useful in making sure that all of the muscles were working correctly.

6) run flex: the main program

When this was selected, the user turns on the hydraulic system, and runs mount until the shoulder is in the correct initial position. Then the user presses the spacebar on the keyboard to start the actual test. For all the tests that we worked on, we ran the test for 6 cycles (i.e. six full cycles of flexion and extension, etc).

7) plot the results

This part of the program sent the graphs of the data to MathCad so the user is able to look at how the muscles worked in each test. It also gave instant feedback on how the motions worked, so that we could adjust the control parameters so that the tests worked as best as they could.

8) edit the tendon location matrix

This was very important because it established the 3-dimensional coordinates of each of the tendons, which ultimately tells the program when and how much to pull on each of the tendons. It was imperative that we measured the x, y and z coordinates of the tendons very carefully.

9) exercise the cylinders

This option allowed us to exercise the hydraulic cylinders before each test so that they worked correctly during the tests. It was important to exercise them for about half an hour prior to each test.

10) exit program

Now that you have a basic understanding of how the program works, I will move onto the actual design and specifications of the shoulder simulator that we built.

Hydraulic Cylinders

There are 9 hydraulic cylinders that are available for applying force to different tendons. They are attached to the table and then connected to the cables that pull on the tendon.

Attachable Shoulder Simulator

With four big bolts, we attach the attachable shoulder simulator to the existing wrist simulator setup, so that we can easily interchange the shoulder simulator and wrist simulator. The base of the attachable shoulder simulator is made of Plexiglas Attached to the Plexiglas base is a vertical piece of aluminum in which there are holes that have been drilled. Through these holes, the seven cables run to pull on the tendons.

Lines of Action

It is important to talk about the lines of actions we chose for the cables to pull on the tendons. After reading Pandy's paper on the Lines of Actions, we compromised and decided on the following lines of action, as seen in Table 2. In saying we compromised, I mean that the lines of action that we chose were not exactly the lines of action from Pandy's paper. However, they were very close. Choosing the correct lines of action is very instrumental in the success of the simulator because if they are incorrect, the tendons will be pulled at the wrong angles, which might in turn move the shoulder in the wrong direction.

Table 2. Lines of Action of Muscles where the line of action is relative to the horizontal with negative degrees being below the horizontal.

Muscle	Line of Action (degree)
Anterior Deltoid	0
Middle Deltoid	0
Posterior Deltoid	0
Supraspinatus	-5
Subscapularis	-16
Teres Minor	-24
Infraspinatus	-36

Figure 1 shows the holes that were designed for the shoulder simulator, corresponding to these lines of action. The cables passed through the holes in the vertical aluminum piece so that the cables ran and pulled the tendons at the specified degrees above. The degrees above are taken with respect to the horizontal, in which negative angles are below the horizontal. Figure 1 shows which holes were used for which muscles on the vertical aluminum piece in which the cables run through.

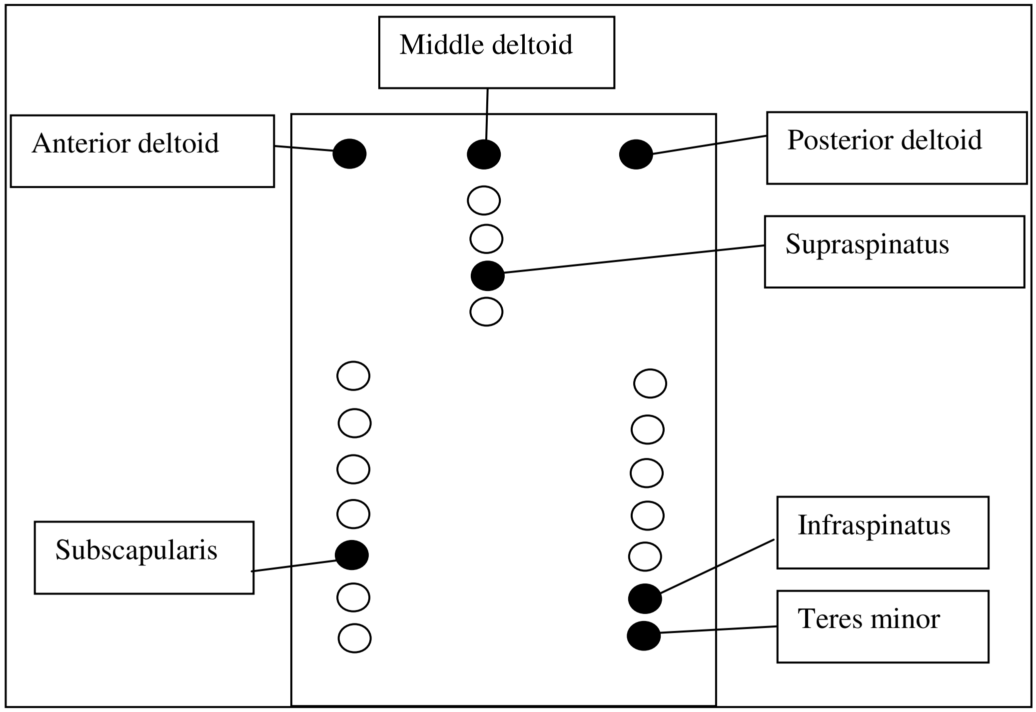

Figure 1. Holes used for Shoulder Simulator

Cable Attachments

Each of the cables run through the aluminum block and then are attached to the tendon with the use of two different types of clamps, cylindrical and square, depending on the size and shape of the tendon. For the larger tendons, we used square clamps and for the smaller tendons, we used the cylindrical clamps.

Pulley System

We spent a lot of time working on the pulley system for the three parts of the deltoid muscle (anterior, posterior and middle). We studied how the deltoids actually work anatomically and then designed a pulley system that achieved the closest representation of those movements. The design we chose has three pulleys hang from an overhang above the shoulder cadaver, specifically the humeral head.

We created the pulley system to be easily adjustable for different shoulders. There is a matrix of holes on the overhand and the pulleys attach to bolts that run through the overhang. These bolts can move up and down as well as be moved between holes on the overhang. Therefore, with this pulley system, we can move the pulleys vertically and horizontally.

Dissecting Shoulders

In order to dissect the shoulders, I had to have a basic knowledge of the muscles and how they look anatomically, using Netter's Atlas of Human Anatomy. In order to dissect correctly, I worked to separate and identify each of the muscles, focusing on the four rotator cuff muscles and the three deltoids. Once I identified each of those seven muscles, I took the muscle off with a scalpel until I found the tendon. Once the tendons were isolated, I worked hard on making them as clean as possible, enough to be able to successfully attach them using the clamps. If they were too slippery, the tendons wouldn't stay in the clamp. Lastly, I worked hard on cleaning the scapula as well, so that I would be able to pot the shoulder in Epoxy successfully.

Potting the Shoulders

In order to pot the shoulders in a repeatable and easy to do manner, we devised a potting method after reading some papers on bony landmarks. We chose to look at three bony landmarks on the shoulder cadaver. We looked at the coracoid process, the acromion and the third point at the root of the scapular spine. We also used the fact from the literature that the normal anatomical resting position for the scapula is ten degrees forward inclination.

The desired position for the shoulder before potting was to have the scapular spine at zero degrees. We also made sure that the degree between the posterior side of the acromion and the coracoid process was at 15 to 20 degrees. These bony landmarks and degrees were based off of past literature.

In order to pot in the correct position, we first set up the scapula in the desired position using screws to hold it in position. Then we pour the Epoxy into the enclosure and wait about an hour until the Epoxy hardens. Then once it is hard enough, we take the cadaver with the Epoxy out of the enclosure so that it is ready for testing.

Care of Shoulder Cadavers

It is very important to take care of the shoulder cadavers. In order to do so, each time we were done testing, I wrapped them in a plastic chuck and placed them in the refrigerator or freezer, depending on when I was going to need to use it next. Sometimes it was important to wrap the tendons in gauze to allow the tendons to dry out so that they were better able to stay in the clamps.

Results

After building the shoulder simulator, I tested a few shoulders but there is only relevant data so far from Shoulders 1 and 2, so for this section, I will talk about the results from each of these shoulders. We used a few other shoulders to figure out how the simulator worked, make it better and get acclimated to testing the shoulder simulator.

Shoulder 1

For Shoulder 1, I performed many tests which included the abduction/adduction, flexion/extension and combined abduction/adduction and flexion/extension motions. From the tests that worked well, I chose the best tests for each of the motions.

Abduction/Adduction (F/E)

For the abduction/adduction test that worked well (fe4), I found that the muscles that acted well were the middle deltoid and supraspinatus. This test had a center of abduction/addction motion of 30 degrees and plus or minus 15 degrees of abduction/adduction motion. Figure 2 shows the actual motion versus the desired motion for abduction and adduction. One can easily see from the graph that they fit together very well for all of the cycles. The desired motion was calculated from the center of abduction/adduction motion as well as the degrees of abduction/adduction motion. From now on, the desired motion always corresponds to the motion that we specified before testing.

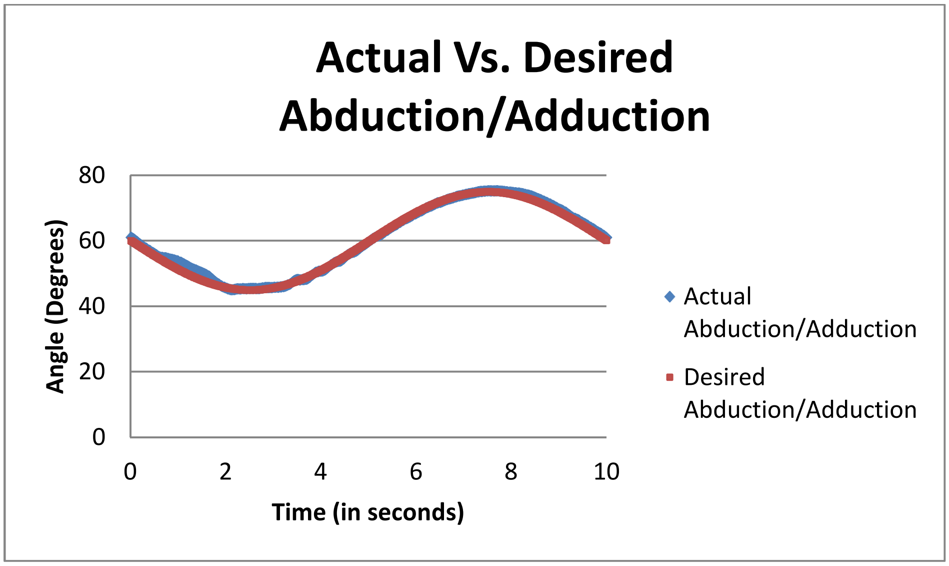

Figure 2. Actual Abduction/Adduction motion (blue) vs. Desired Abduction/Adduction (pink)

Figure 3 shows the forces of the deltoid muscles. It is quite clear that the middle deltoid (in blue) is very active during abduction while the anterior and posterior deltoids are semiactive during abduction and adduction.

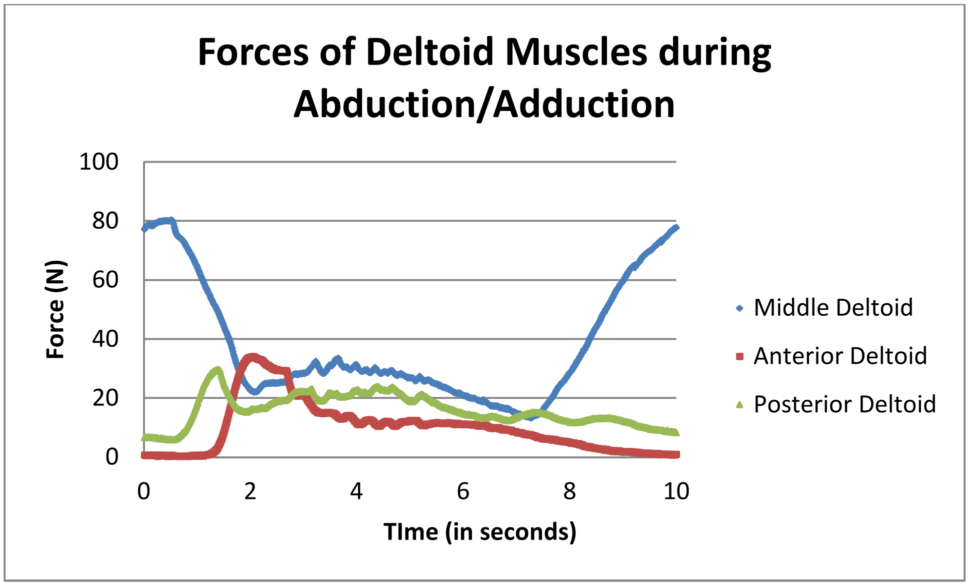

Figure 3. Forces of Deltoid Muscles During Abduction/Adduction

Figure 4 shows the forces of the four rotator cuff muscles. As one can see, there is a spike in supraspinatus activity during abduction and mild activity for all of the other rotator cuff muscles.

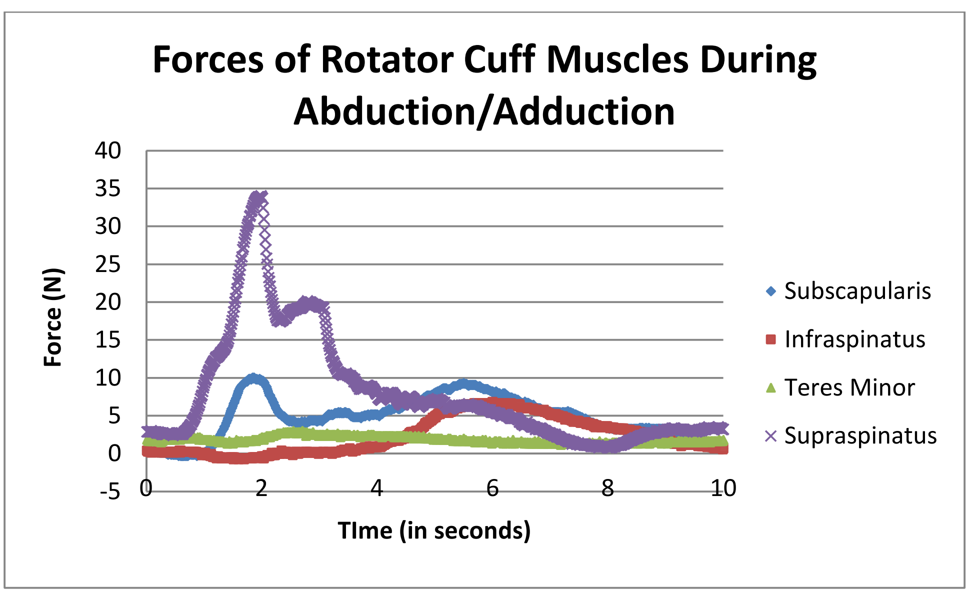

Figure 4. Forces of Rotator Cuff Muscles During Abduction/Adduction

Shoulder Flexion/Extension

For the flexion/extension motions, I looked at one of the tests in which most of the muscles worked well (ru15). For this test, the center of abduction/adduction motion was 30 with plus and minus 15 degrees of flexion/extension. In this test, as one can see from the following figures, the subscapularis, middle deltoid and subscapularis worked like they are supposed to.

Figure 5 shows the desired flexion/extension versus the actual flexion/extension. One can see that the actual motion went a little further into flexion than the desired extension. However, the graphs are very closely correlated.

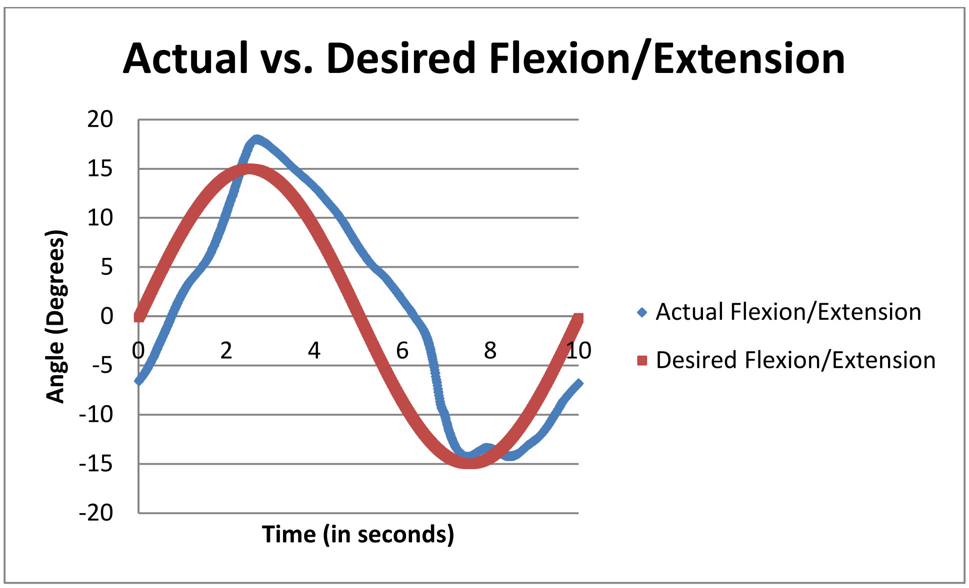

Figure 5. Desired Internal/External Rotation vs. Actual Internal/External Rotation

Figure 6 shows the forces of the deltoid muscles during flexion/extension. Note that the first half of each cycle is flexion, followed by extension. One can see that the middle deltoid was active during extension, while the anterior and posterior deltoids are semiactive during the entire test.

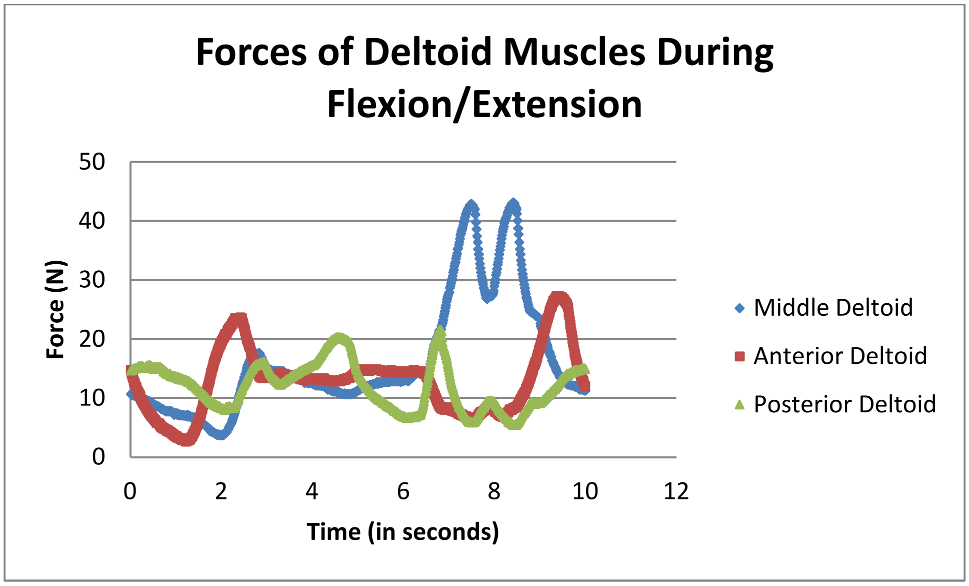

Figure 6. Forces of Deltoid Muscles During Internal/External Rotation

Figure 7 shows the forces of the four rotator cuff muscles during flexion and extension. As one can see from this graph, the subscapularis exerts a lot of force to move the shoulder during flexion. The infraspinatus and teres minor also exert minor force to the shoulder during flexion. Something else that can be noted from this graph is that the subscapularis and infraspinatus exert minor forces on the shoulder during extension.

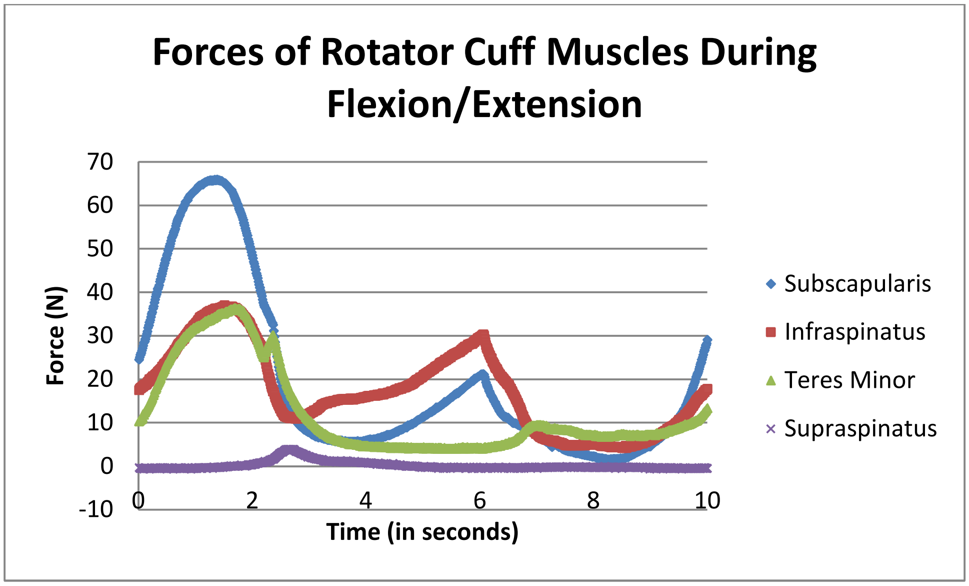

Figure 7. Forces of Rotator Cuff Muscles During Internal/External Rotation

Combined Abduction/Adduction and Flexion/Extension

For the combined motion, I once again looked at the test with most of the muscles working correctly (rufe3). In this test, the center of abduction/adduction was 30 degrees. Also, there was plus and minus 15 degrees of abduction/adduction as well as plus and minus 15 degrees of flexion/extension. For the first half of the cycle, the shoulder moved into abduction and flexion and during the latter half of the cycle, the shoulder moved into adduction and extension.

Since there was both abduction/adduction and flexion/extension, we are going to examine the graphs for both of those motions to see how well the desired and actual motions were correlated.

Figure 8 shows the graph for the desired vs. actual abduction/adduction motions. As one can see, the shoulder fully abducted, but did not fully adduct. There are possible explanations for this, including the actuators "bottoming out" so that they couldn't pull the cable any further.

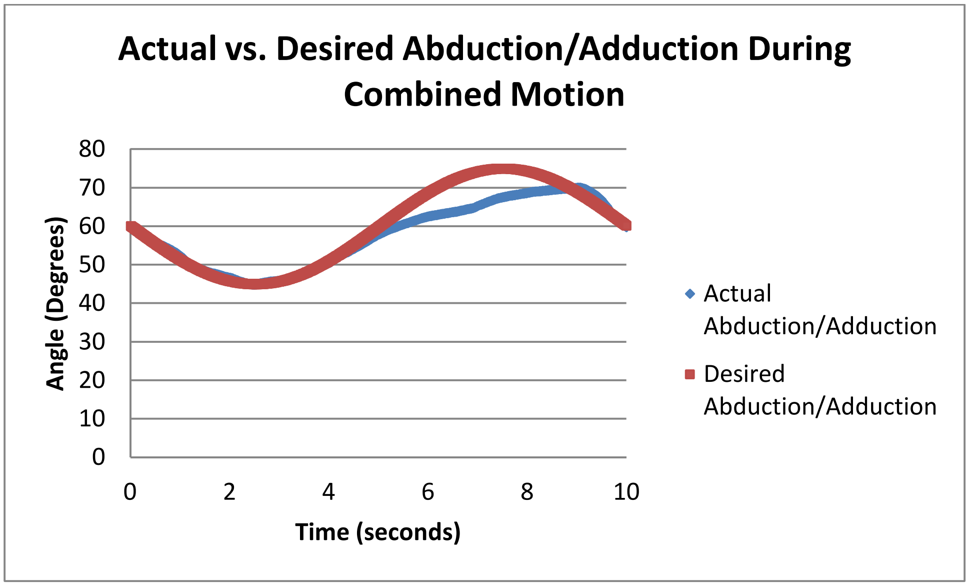

Figure 8. Actual vs. Desired Abduction/Adduction

Figure 9 shows the graph for the desired vs. actual flexion/extension motions. While this graph is a little messier than the others, it was the closest correlation of desired vs. actual flexion/extension among the combined motion tests done on Shoulder 1. One can see that the shoulder went fully into flexion but struggled to move fully into extension. Again, there are explanations for this, including that the cables couldn't pull any further. On future tests, we hope to fix any of these issues that we encountered on these first two shoulders that have been tested.

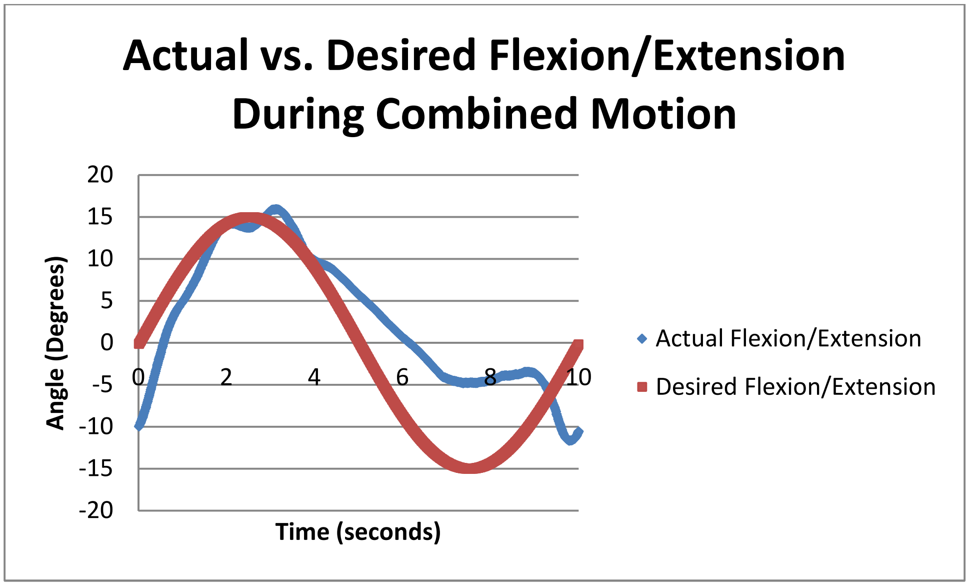

Figure 9. Desired vs. Actual Flexion/Extension

Figure 10 shows the forces of the deltoid muscles during the combined motion. It is important to note that the beginning of the cycle is when the shoulder moved into abduction and flexion, while the second half of the cycle is when the shoulder moved into adduction and extension. One can see that the middle and anterior deltoid were very active during the abduction and flexion, while the posterior deltoid remained semi active during the whole test.

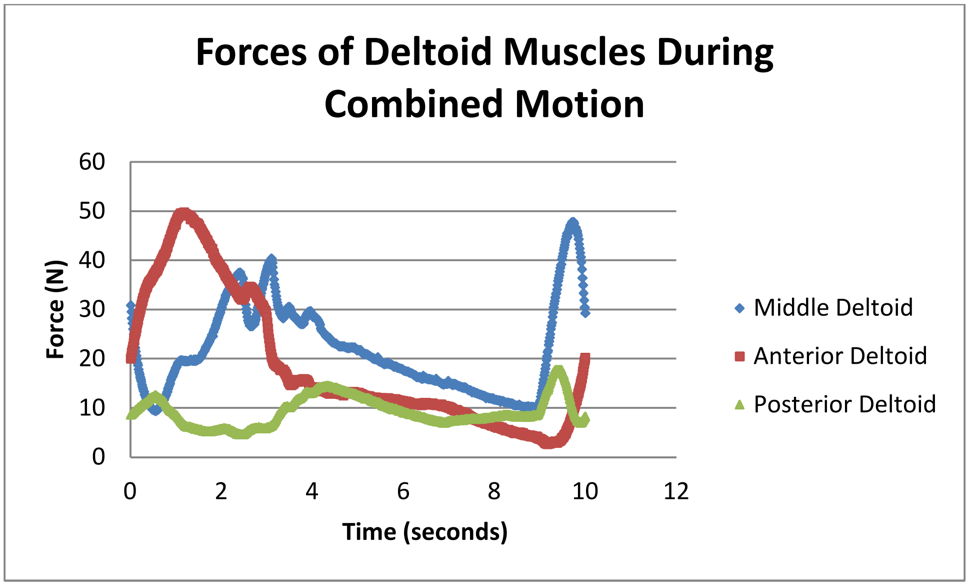

Figure 10. Forces of Deltoid Muscles During Combined Motion

Figure 11 shows the graph of the forces of the rotator cuff muscles during the combined motion. It is easy to see that the infraspinatus exhibited more activity in the second half of the cycle, while the teres minor was more active during the first half of the cycle. The supraspinatus exhibited minor spikes in activity during the abduction and flexion. Lastly, the subscapularis was active during both of the parts of the cycle.

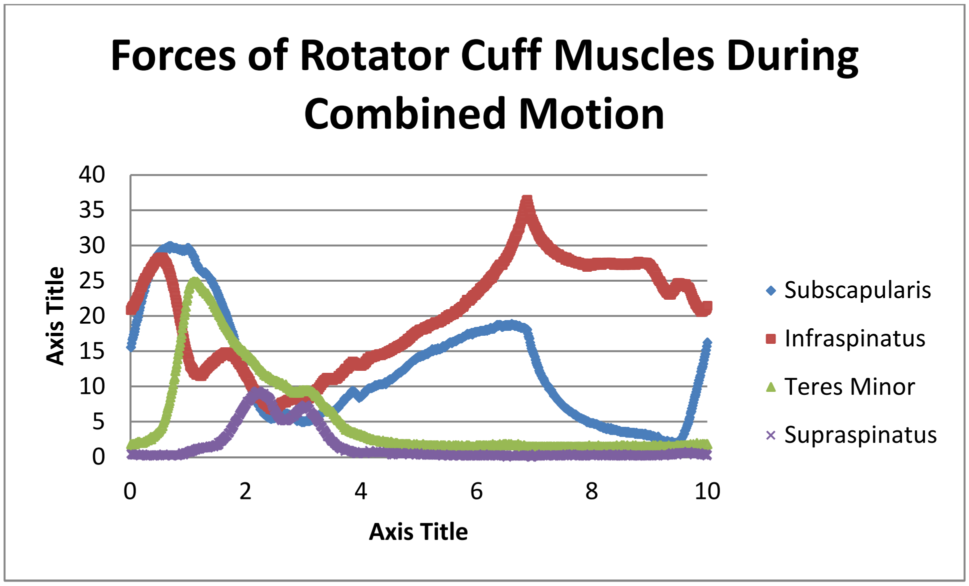

Figure 11. Forces of Rotator Cuff Muscles During Combined Motion

Shoulder 2

For Shoulder 2, I also performed many tests and then from those tests determined which tests had the most muscles that worked correctly.

Abduction/Adduction

For abduction/adduction, the test that I decided had the most muscles that worked (fe25a) had a center of abduction/adduction of 50 degrees and had plus and minus 25 degrees of abduction/adduction. Figure 12 shows the graph of the desired vs. actual abduction/adduction motions. As one can see, the shoulder went fully into abduction, but didn't make it fully into adduction. Note that this may be because the range of motion for this test was larger than previous tests (+/- 25 degrees). We are aiming for at least 15-20 degrees of abduction/adduction.

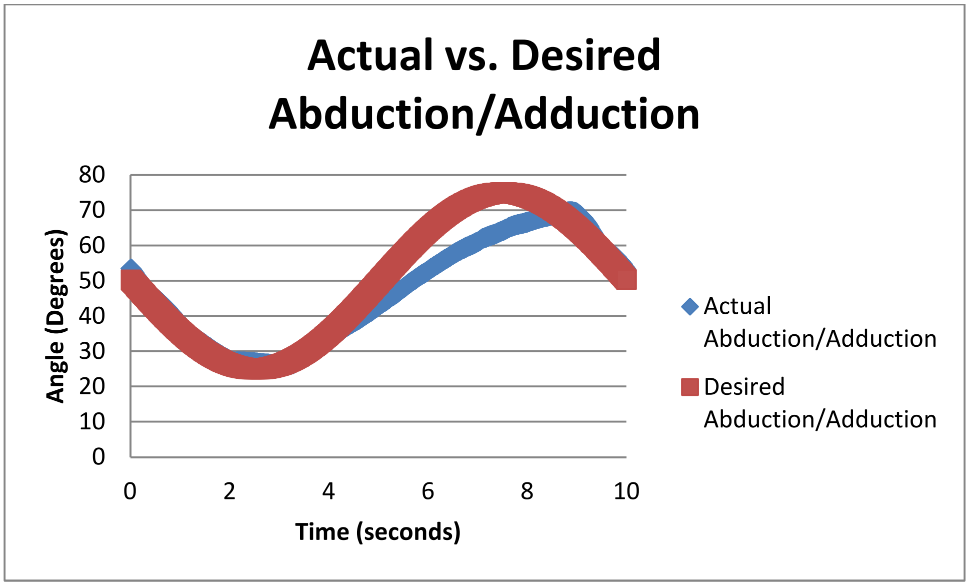

Figure 12. Desired vs. Actual Abduction/Adduction

Figure 13 shows the forces of the deltoid muscles during abduction/adduction. It is easy to see that the middle deltoid was very active during abduction while the posterior and anterior deltoids were semi active during the entire test.

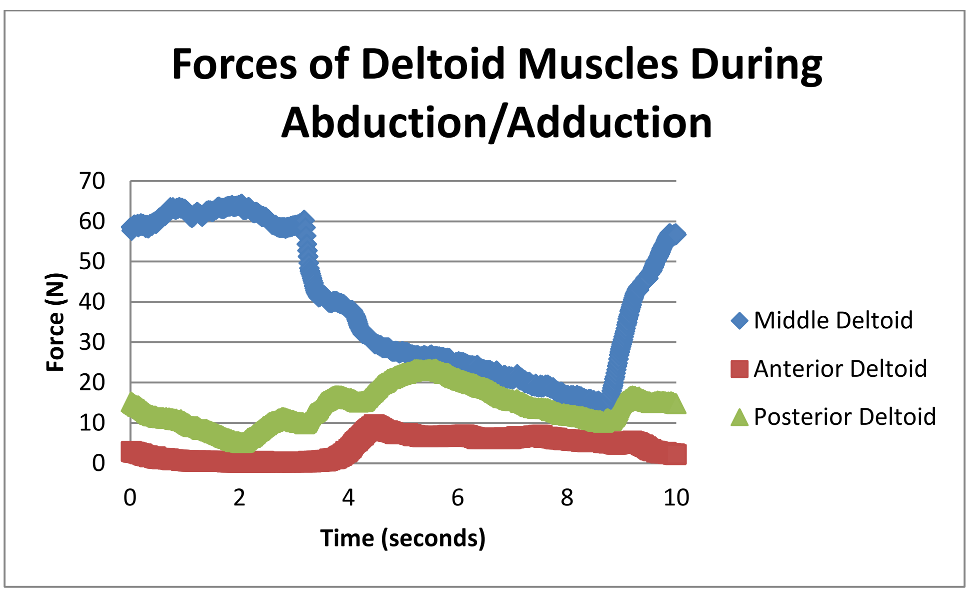

Figure 13. Forces of Deltoid Muscles During Abduction/Adduction

Figure 14 shows the forces of the rotator cuff muscles during abduction/adduction. It is clear from this graph that the supraspinatus was very active during both the abduction and adduction, while the subscapularis exhibited a lot of activity during adduction. The infraspinatus was active in the first cycle during adduction, but then dropped off. Lastly, the teres minor was semi active during the entire test.

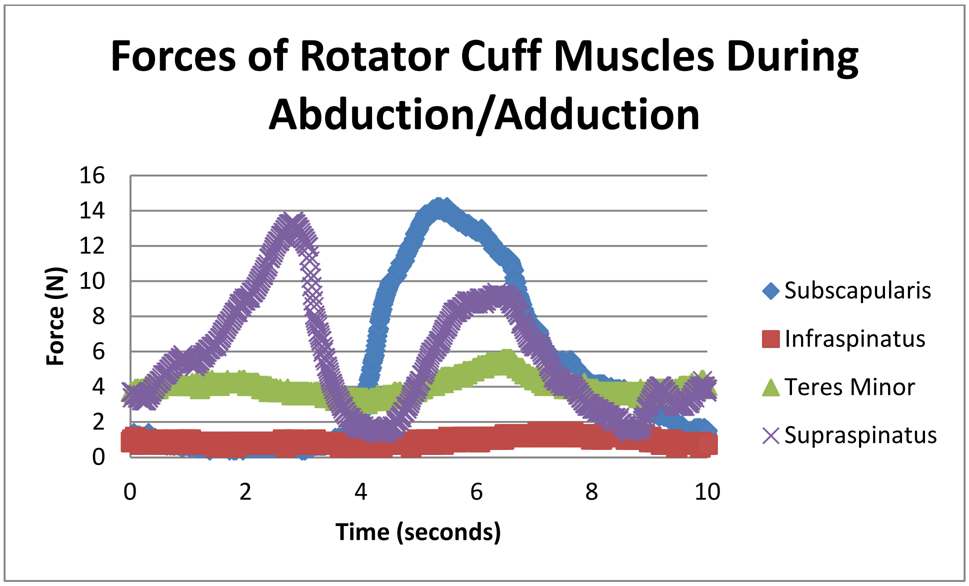

Figure 14. Forces of Rotator Cuff Muscles During Abduction/Adduction

Flexion/Extension

For the flexion/extension test that worked well (ru20a), there was a center of F/E motion of 55 degrees with plus and minus 20 degrees of flexion/extension.

Figure 15 shows the graph of the desired vs. actual flexion/extension motion. It is easy to see that the actual flexion/extension motion made it fully into flexion as well as fully into extension. However, there was a minor delay.

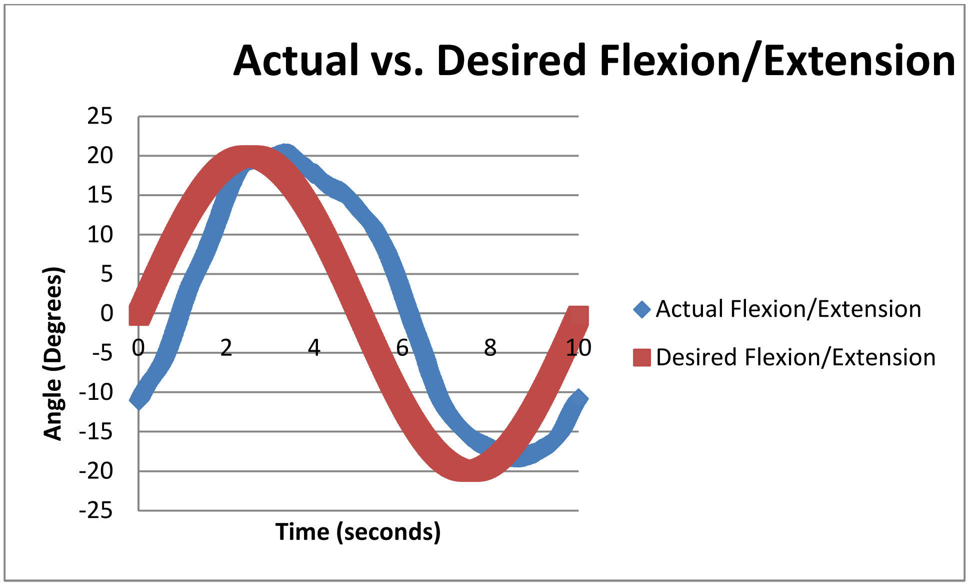

Figure 15. Desired vs. Actual Flexion/Extension

Figure 16 shows the forces of the deltoid muscles during flexion/extension. One can see that the middle deltoid was active throughout the entire test. However, the anterior deltoid was more active during flexion and the posterior deltoid was more active during extension.

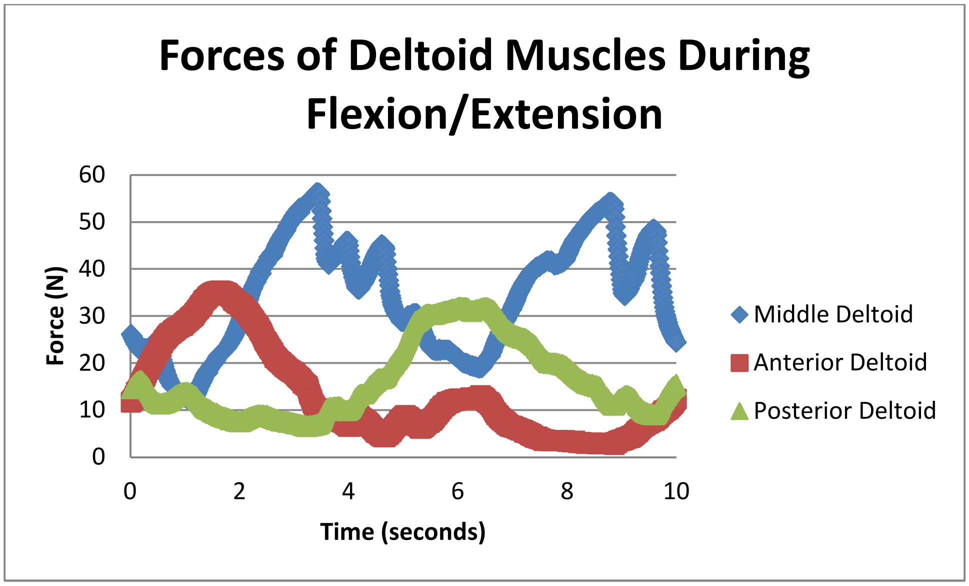

Figure 16. Forces of Deltoid Muscles During Flexion/Extension

Figure 17 shows the forces of the rotator cuff muscles during flexion/extension. The subscapularis and infraspinatus were active during the entire test, while the teres minor was more active during flexion. Lastly, the supraspinatus was barely active at the beginning of the test and then dropped off.

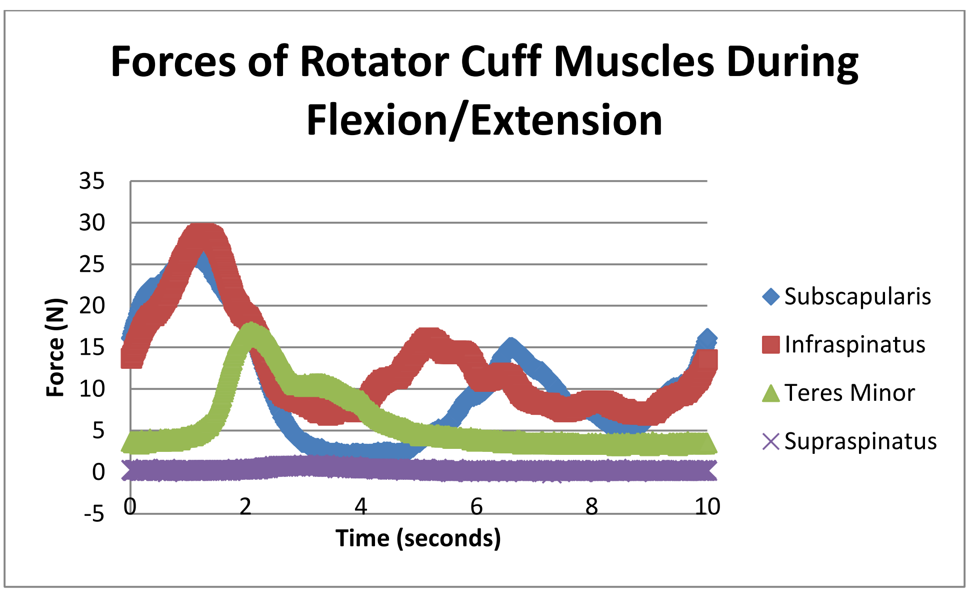

Figure 17. Forces of Rotator Cuff Muscles During Flexion/Extension

Combined Motion

For the combined motion test that worked the best for Shoulder 2 (dart15c), the center of F/E motion was 45 degrees. Also there was a plus and minus 15 degrees of abduction/adduction along with plus and minus 15 degrees of flexion/extension.

Figure 18 shows the desired vs. actual abduction/adduction motion during this test. One can easily note that the two curves are greatly correlated, meaning that the shoulder moved fully into abduction as well as fully into adduction.

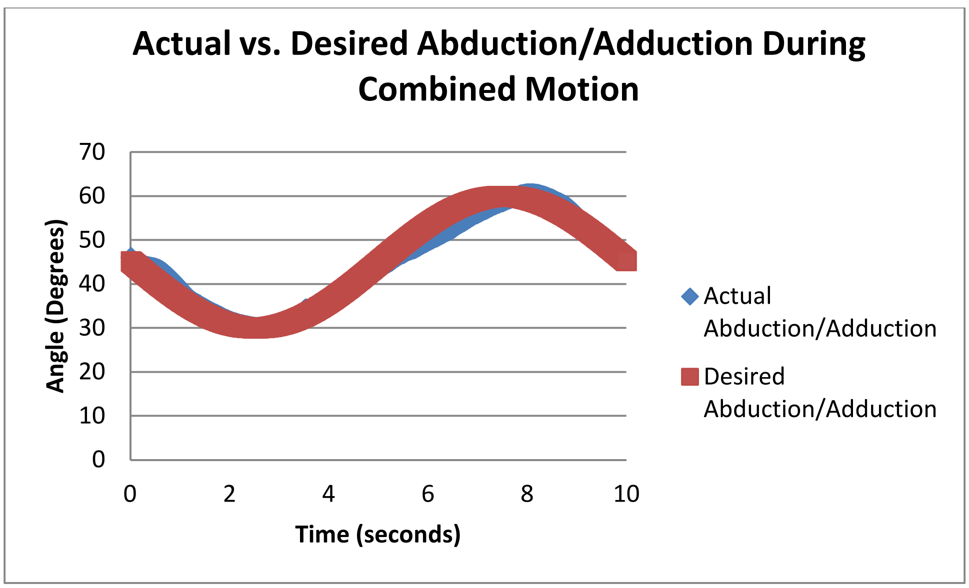

Figure 18. Desired vs. Actual Abduction/Adduction

Figure 19 shows the desired vs. actual flexion/extension motions. The shoulder went fully into flexion (after a bit of a struggle) and then went fully into extension (a bit delayed).

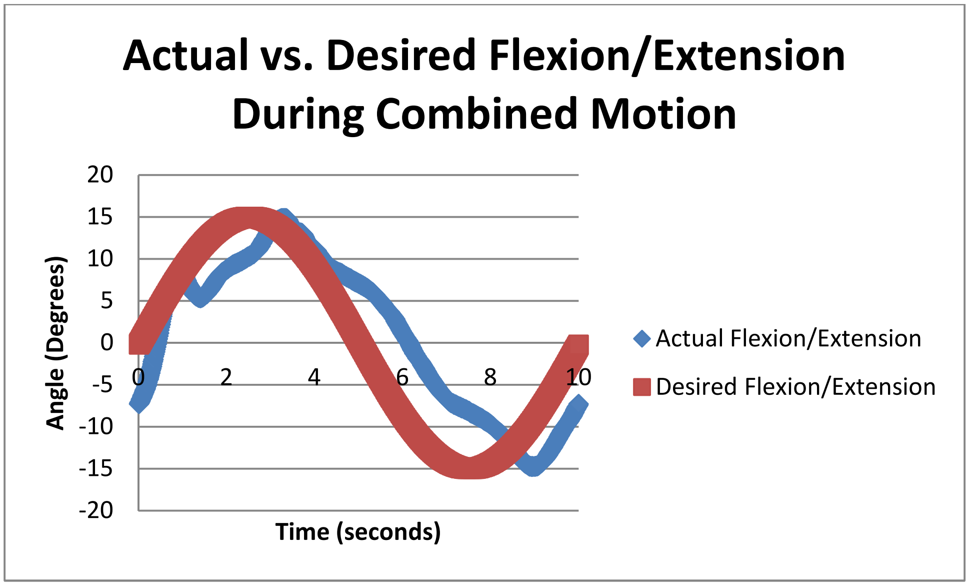

Figure 19. Desired vs. Actual Flexion/Extension

Figure 20 shows the graph of the forces of the deltoid muscles during the combined motion. The middle and anterior deltoids were very active during the first half of the cycle (abduction/flexion), while the posterior deltoid maintained minor activity during the entire cycle.

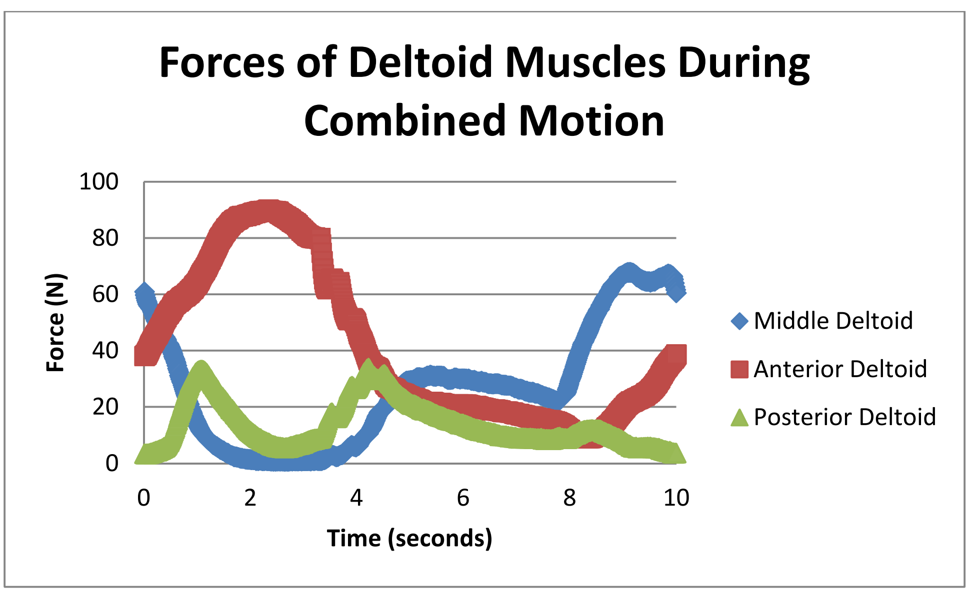

Figure 20. Forces of Deltoid Muscles During Dart Motion

Figure 21 shows the forces of the rotator cuff muscles during combined motion. The subscapularis and infraspinatus were active during the second half of the cycle (adduction/extension) while the teres minor and supraspinatus were more active during abduction/extension. This is what we would expect regarding the muscles.

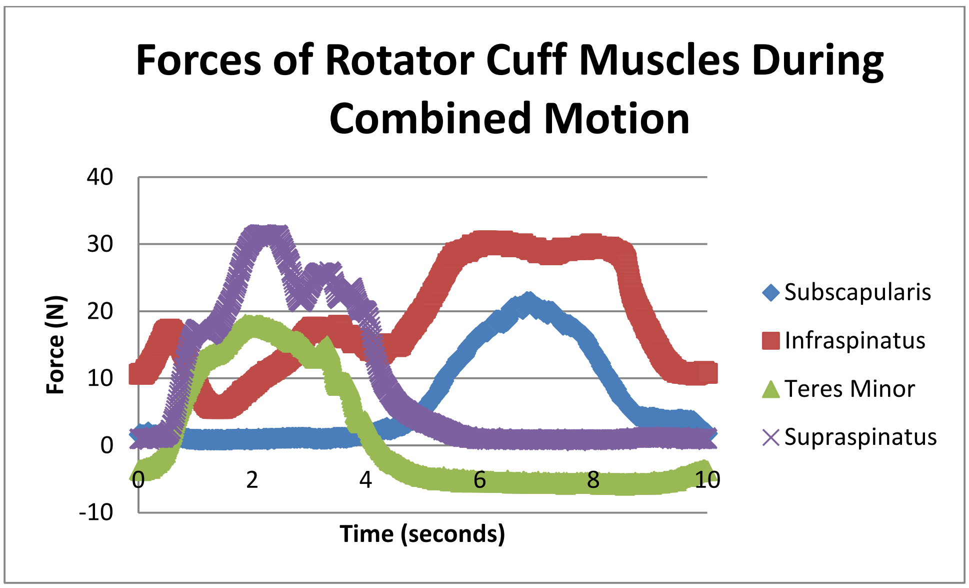

Figure 21. Forces of Rotator Cuff Muscles During Dart Motion

Discussion

The preliminary tests using the shoulder simulator which we designed and built show that there is a lot of promise in the new design. Many of the shoulder muscles worked correctly, as one can see in the graphs in the Results section. Many of the muscles were active at the correct times during the tests. This was assessed using the past literature which told us which muscles were movers and which muscles should be active during the specified motions. However, there were a few issues in each test that hopefully can be fixed with future tests using the existing shoulder simulator.

In all, we have devised a repeatable and reliable plan regarding how shoulders are dissected, potted and tested based off of my literature review as well as experience in the actual experiments. Through our experiments, we have seen what works and what does not work and devised plans on how to correct the evident issues. During future tests, we will take into consideration the issues, but overall, the shoulder simulator works well and can be used in future experiments.

In future experiments, one could put implants in the shoulder cadavers and then study how the implants work in various motions. One could also test the viability of the implants through cycle testing. The shoulder simulator could make the shoulder go through a set of motions hundreds of times to find the mean time between failures of the implants.

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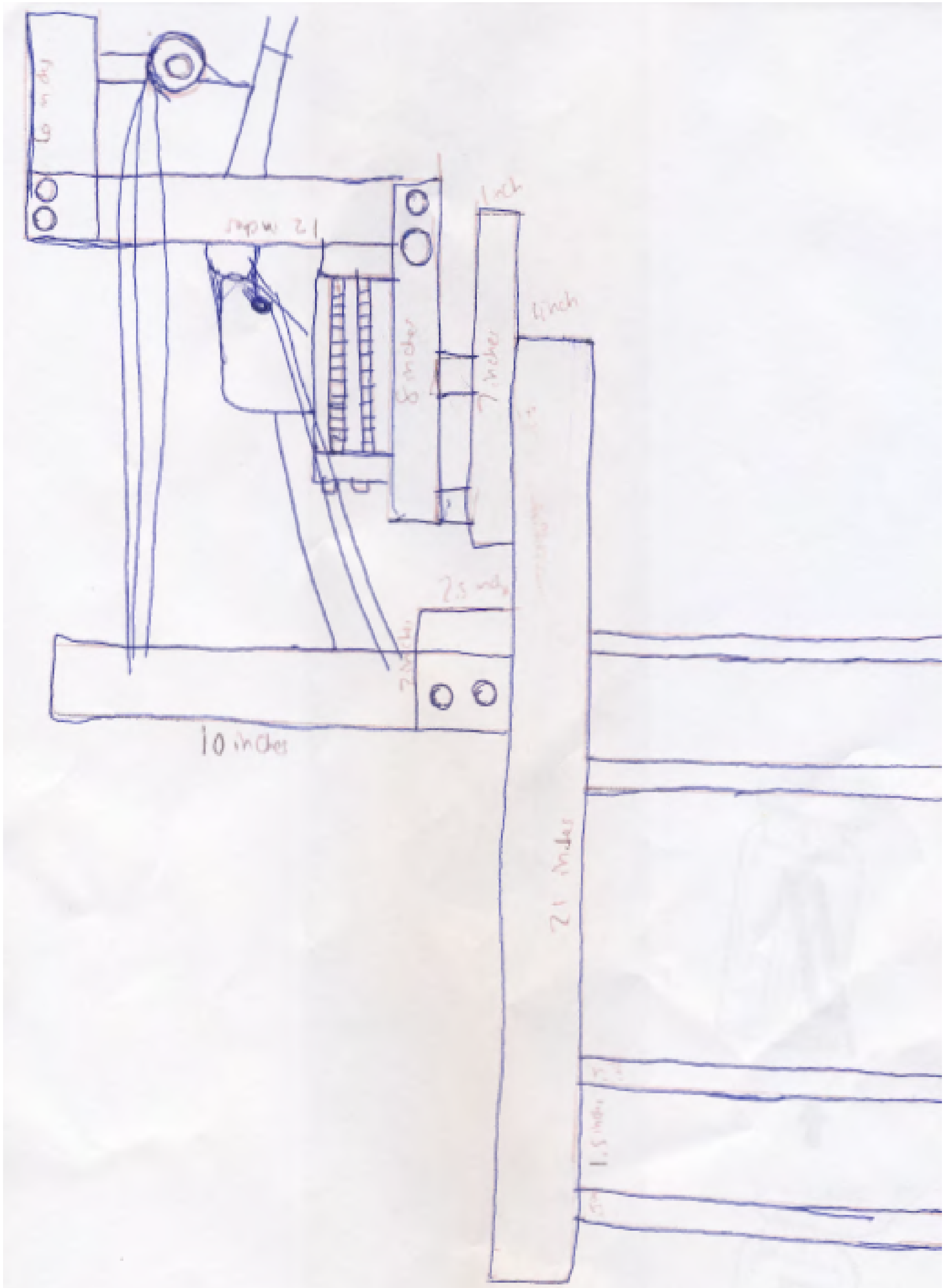
Appendix A. Mechanical Drawing of Shoulder Simulator



Capstone Summary

People use their shoulder for many different functions during any given day. The shoulder is hard to stabilize and is prone to a lot of injury. Thus, it is easy for a shoulder to have issues, such as rotator cuff tears. For my Honors Capstone project, I have built a shoulder simulator that can be used to study the shoulder, specifically the rotator cuff and deltoid muscles. The simulator also can be used to study shoulder implants and how they work in the shoulder.

To give you more background on the shoulder and the motions we focused on, I will briefly explain the rotator cuff muscles and the motions. The supraspinatus, infraspinatus, teres minor and subscapularis are the 4 rotator cuff muscles. They run around the humerus and help to stabilize the shoulder. There are three main bones in the shoulder: the scapula, clavicle and the humerus. The humerus is the upper part of the arm. The motions that I focused on for my project were abduction/adduction, flexion/extension and a combined motion which combined abduction/adduction and flexion/extension. Abduction is when someone moves their arm away from their body to the side. Adduction is when someone brings their arm close to their body from the side. Forward flexion is when someone moves their arm in a forward motion in front of their body. Extension is the opposite: when someone moves their arm behind them.

For this model, we used a program to control actuators that pull on cables, which in turn pull on the tendons of shoulder cadavers that we dissected. The program tells the actuators which tendons to pull on in order to get a given motion in the shoulder.

To achieve the goal of this project, I had to read literature on shoulder simulators, dissect multiple shoulder cadavers, design and build the shoulder simulator, test various shoulders using the simulator and finally, and evaluate the simulator by studying the graphs and figuring out which muscles worked well and which didn't. To date, I have successfully tested and performed data analysis on two shoulders and am working on testing more. In all, we would like to have around eight shoulders tested using the simulator.

The papers that I looked at throughout my literature review gave me the necessary background to successfully identify the functions of the seven shoulder muscles that we are focusing on. Pandy et. al also gave us information on the lines of action of the muscles which was critical in our simulator design. The lines of action that we found corresponded to the location of the holes for the cables to run through when they pull on the tendons. It is critical that we have the lines of action correct because if we don't have them correct, the muscles could end up doing the wrong thing, i.e. supraspinatus acting as a mover instead of not being active at all.

Another major part of our design was the formation of a pulley system to pull on the deltoid tendons. We created a design that was easy to modify yet worked correctly, meaning it pulled the humerus in the right directions. Our pulley system turned out to work very well and was easy to manipulate.

The control theory of the shoulder simulator is also used in wrist simulator applications and is fairly easy to use. In the program, there is a file in which one can modify the control parameters, such as the center of rotation and feedback gains. It is important to be able to easily modify the feedback gains, because we can essentially make the simulator work better by modifying the gains. There also is a file in which we can modify the positions of all the tendons and this allows the program to know where the tendons started and tells it where and when to pull on that tendon. It is critical that these positions be correct as well, because the wrong positions will make the program tell the actuators to pull on the tendons at the wrong time, thus leading to an incorrect motion.

Also, within the program, we can plot the results. This was very important for us, since we could quickly know how the simulator was performing. The program transfers the data to MathCad, which then shows us the graphs for all of the muscles. From these graphs, we can see if the muscles were doing what they are supposed to do based off of past literature using shoulder simulators.

While preparing the shoulder cadavers for testing in the shoulder simulator, it was important to be careful when dissecting the tendons. I tried to get as much tendon as possible. The tendons needed to be able to be clamped onto. Once the shoulders were dissected correctly and thoroughly, we potted the shoulders using a repeatable and reliable technique. Using various papers from the shoulder simulator literature, we designed a way to pot the shoulders for successful use in the simulator. It is very critical to have the shoulders potted in a correct manner, because if they aren't, that could easily lead to problems during testing, such as incorrect motions.

There currently is relevant data on two of the shoulders, A and B.
For shoulder A abduction/adduction, we used a center of abduction/adduction of 30 degrees with +/- 15 degrees of abduction/adduction. The muscles that worked well were the middle deltoid and the supraspinatus. For the flexion/extension motion, we used a center of abduction/adduction of 30 degrees with +/- 15 degrees of flexion/extension. The muscles that worked well were the subscapularis, middle deltoid and subscapularis. Finally, for dart motion, which is a combination of abduction/adduction and flexion/extension, we used a center of abduction/adduction motion of 30 degrees with +/- 15 degrees of FE and RU. The muscles that worked well were the infraspinatus, middle deltoid, anterior deltoid, subscapularis, teres minor and supraspinatus. The take away message from these results is that many of the muscles worked well in the shoulder simulator.

For Shoulder B we used similar values to achieve successful motions of the shoulder in the simulator. For abduction/adduction motion, the center of motion was 50 degrees with +/- 25 degrees of abduction/adduction. The muscles that worked well were the middle deltoid, supraspinatus, posterior deltoid, infraspinatus, and subscapularis. For flexion/extension motion, the center of motion was 55 degrees with +/- 20 degrees of flexion/extension. The muscles that worked well were the middle deltoid, subscapularis, and infraspinatus. For the combined motion, the center of abduction/adduction motion was 45 degrees with +/- 15 degrees of abduction/adduction and flexion/extension. The muscles that worked well were the anterior deltoid, middle deltoid, supraspinatus, and infraspinatus.

One can see that many of the muscles worked correctly in the shoulder simulator, which tells us that the simulator works pretty well at creating the correct motions and pulling on the correct muscles. Most of the muscles do what they are supposed to. As we continue to work on the shoulder simulator, we are striving to make it better. We would like to have all the muscles working correctly. We are carefully considering which muscles worked well and which muscles didn’t work well during our initial tests.