KIN 4GG3: Clinical Biomechanics
Assignment #3: Simulating Tendon Transfer Options for Rotator Cuff Tears

Date released: October 18, 2021 | Date Due: November 1, 2021 (11:59 PM)

Submission Guidelines

- 40 marks total
    - PDF of written report submitted directly to Avenue

Note: all the files (model, plugin, motion, tutorial videos) are available to download from the class Google Drive (link provided below).

https://drive.google.com/drive/folders/1WDNAGF4ttKzCjgOSI5OUYh6hge5wA1D-?usp=sharing

Overview:
You will be using a computational shoulder musculoskeletal model available in OpenSim 4.1 to evaluate the functional roles of glenohumeral muscles during a frontal plane abduction motion, assess the possible consequences of posterior-superior rotator cuff tears of different severities, and simulate options for tendon transfers to restore shoulder function following a full thickness tear of the supraspinatus and a large thickness tear of the infraspinatus.

Purpose:
To develop practical skills in computational biomechanics, applying knowledge of musculotendon mechanics and musculoskeletal geometry to address clinically relevant problems, and advancing your ability to analyze, report, and interpret data.

Model and Data:
OpenSim is an open-source software for computational biomechanical modelling, simulations, and analysis of human and animal movement. OpenSim can be used for several different purposes, including inverse dynamics and forward dynamic simulations. OpenSim is the most commonly used modelling software by biomechanists around the world and is regularly updated with new developments, pushing the boundaries of computational biomechanics. It really is an amazing software and I encourage you to go through their website on the potential uses of the software: https://simtk.org/projects/opensim/

For this assignment, we will use a recently developed shoulder model (Seth et al., 2019). The model includes 6 segments – thorax, clavicle, scapula, humerus, ulna, and radius – as well as 33 muscles/muscle regions. The musculotendon parameters (maximal isometric strength, pennation angle, tendon slack length, optimal fibre length) and musculoskeletal geometry (attachment locations of muscles, joint axis locations to define muscle moment arms, kinematic capabilities) of the model are based on cadaveric data. Although we will not be using the model to specifically perform inverse or forward dynamics type of simulations, we will use the model to introduce how musculotendon mechanics and musculoskeletal geometry can be implemented in a biomechanical model to study the functional roles of muscles. In addition, we will simulate "what if" scenarios using the computational model to study the consequences of rotator cuff tears as well as investigate tendon transfer options to replace the function of the damaged rotator cuff muscles. The assignment will specifically focus on frontal plane abduction. The kinematic data inputted into the model was originally from bone pin data (Ludewig et al., 2009). If you are interested in learning more about the model or the kinematic data (the latter being a paramount study in shoulder kinematics), the references are cited below:

Ludewig, P. M., Phadke, V., Braman, J. P., Hassett, D. R., Cieminski, C. J., & LaPrade, R. F. (2009). Motion of the shoulder complex during multiplanar humeral elevation. *The Journal of Bone and Joint Surgery (American Volume)*, 91(2):738.

Seth, A., Dong, M., Matias, R., & Delp, S. L. (2019). Muscle contributions to upper-extremity movement and work from a musculoskeletal model of the human shoulder. *Frontiers in Neurorobotics*, 13:90.

Part 1:

Your **first goal** is to identify the function of the shoulder muscles at the glenohumeral joint throughout a frontal plane abduction motion. Specifically, you are asked to identify which muscles are "abductors" or "adductors" and which muscles are "internal rotators" or "external rotators" of the humerus at the glenohumeral joint. The following steps will help you accomplish this goal:

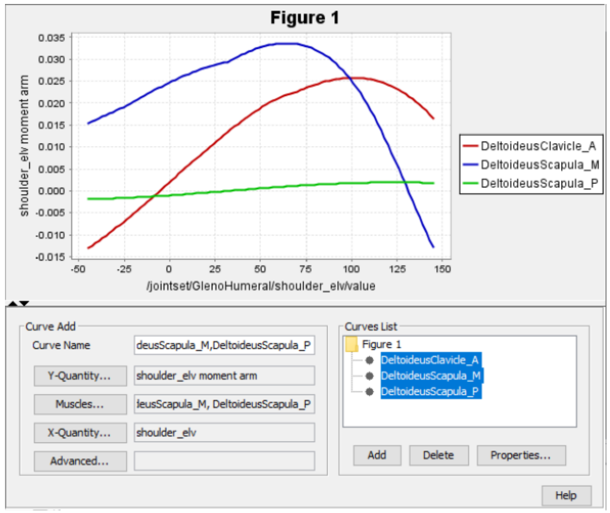
1. Watch the following videos:

1A_opening_the_shoulder_model_windows (Windows users only)
1B_opening_the_shoulder_model_mac (Mac users only)
2_introducing_the_shoulder_model
3_plotting
4_loading_motion

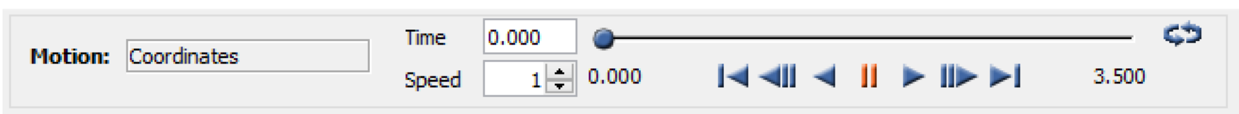
2. Open model *ThoracoscapularShoulderModelSubject.osim* into OpenSim. Note that you *may* have to load the user plugin prior to being able to open the model as explained in video 1A (Windows users) and 1B (Mac users).

3. Familiarize yourself with the shoulder model. Specifically, examine the kinematic capabilities of the model by moving the joints in the *Coordinates* window. While moving the joints, have a note at the corresponding direction of motion with positive and negative values at each joint axis. You will notice that some joint motions are locked and unable to move (e.g., elbow flexion-extension and pronation-supination). Also take the time to identify and familiarize with the different muscles that are part of the model. To move around with the model:
    a. Zooming in-out: scroll wheel
    b. Translate up-down and left-right: hold the right click of your mouse and move up-down and left-right
    c. Rotate around: hold the left click of your mouse and move your mouse.

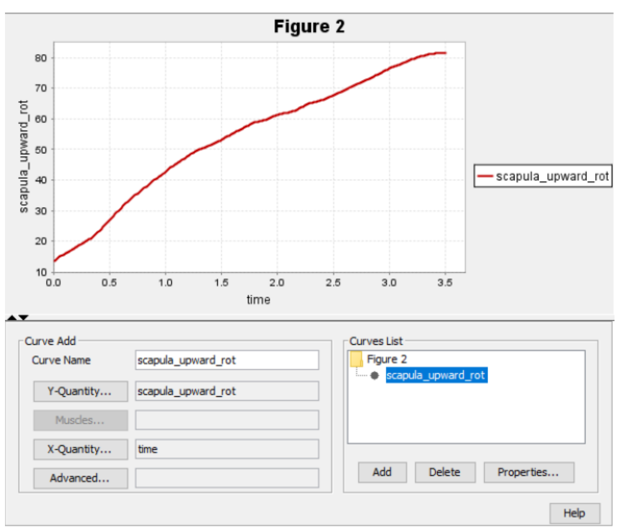
4. Familiarize yourself with plotting different parameters by clicking on Tools > Plot. For example, try plotting out moment arms for specific muscles throughout the range of motion at different joints. To determine the shoulder_elv moment arms for the anterior, middle, and posterior deltoids throughout the shoulder_elv range of motion in the default posture, you can select the following and will get the associated figure:
    a. Y-quantity: shoulder_elv moment arm
    b. Muscles: DeltoideusClavicle_A, DeltoideusScapula_M, DeltoideusScapula_P
    c. X-Quantity: shoulder_elv



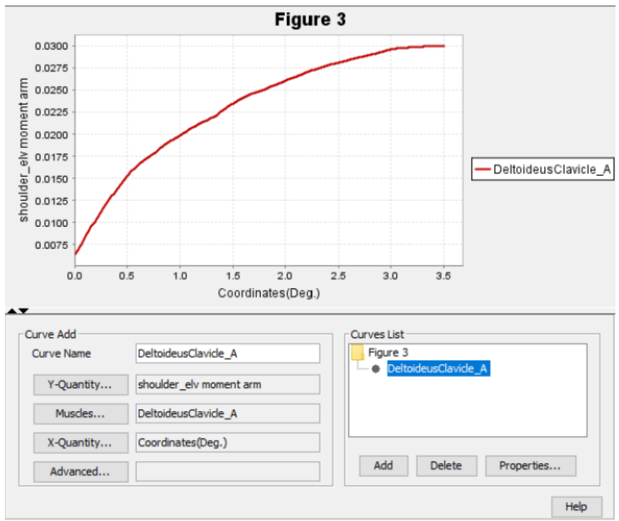
5. Prescribe a frontal plane abduction motion to the model by clicking on File > Load Motion and selecting the *Abduction01_filtered.mot* file. This file has position and orientation information for all the joints during a frontal plane abduction motion that was collected through bone pin data. You can visualize the motion by playing around with the controls in the following panel:



6. To determine the joint angles of different joints throughout this frontal plane abduction motion, you can plot them out over time. For example, the scapula_upward_rot angle can be determined by doing the following, giving you the associated figure:
    a. Y-quantity: Coordinates(Deg.) > scapula_upward_rot
    b. X-quantity: time



7. Once the motion is loaded, to determine the moment arms at a specific joint axis <u>during</u> this motion, you can do so by selecting the X-Quantity as: *Coordinates(Deg.)*. For example, the shoulder_elv moment arm for the anterior deltoid during this motion can be obtained by doing the following, which will allow you to get the figure at the top of the next page. Note that the x-values here represent time (0 to 3.5 seconds of the motion).
    a. Y-quantity: shoulder_elv moment arm
    b. Muscles: DeltoideusClavicle_A
    c. X-quantity: Coordinates(Deg.)



8. Based on the above, determine the muscles that can be considered "abductors" and "adductors" of the humerus by examining their functional role to elevate/lower the humerus (shoulder_elv) during frontal plane abduction. You can use the common names of these muscles as I identify in the video rather than the model names. Similarly, determine the muscles that can be considered as "external" and "internal" rotators of the humerus. If a muscle has both abduction and adduction roles (or both internal and external rotation) depending on the shoulder orientation throughout this motion, please make note of that. The <u>**ONLY**</u> exceptions to this are the infraspinatus and subscapularis, so I have given them to you in the table below and treat them as such for the remaining assignment. Report your observations for the remaining muscles in Table 1.

To give a hint, I will give you the number of muscle regions you should have listed in each section of Table 1, as any errors in Table 1 will impact the rest of the assignment. To make it clear, I am treating separate regions of muscles as two separate entities in my counts here. For example, the biceps long head and biceps short head would be treated as 2 individual muscle regions. Or the superior, middle, and inferior subscapularis would be treated as 3 different muscle regions. Given all of that, you should expect to have 9 muscle regions for abduction, 14 for adduction, 12 for internal rotation, and 13 for external rotation in Table 1.

Table 1: [Insert a relevant and <u>specific</u> table caption here in your report].

Abduction-Adduction	
Abductor	Adductor
Infraspinatus (superior, inferior)	Subscapularis (superior, middle, inferior)
[Insert other muscles]	*[Insert other muscles]*
Muscle A	*Muscle B (superior region)*
Muscle B (inferior region)	*Muscle D (mid-late abduction)*
Muscle D (early abduction)	

Internal-External Rotation	
Internal Rotation	External Rotation
Subscapularis (superior, middle, inferior)	Infraspinatus (superior, inferior)

Part 2:

Your **second goal** is to simulate a rotator cuff tear and evaluate the functional consequences to move our arm in the frontal plane. Rotator cuff tears can range from partial thickness tears of the supraspinatus in isolation to more severe full thickness tears involving the entire cuff (supraspinatus, infraspinatus, teres minor, and subscapularis). In this section, we will investigate different severities of posterior-superior rotator cuff tears, which most commonly affect the supraspinatus and infraspinatus. Specifically, we will investigate the cases listed below from a healthy individual (Case 1) progressing to severe posterior-superior rotator cuff damage (Case 3). We can simulate rotator cuff tears by altering the maximal isometric strength of affected muscles. Consider a <u>partial thickness tear as a muscle at 40% of its typical isometric strength</u>, a <u>large thickness tear as a muscle at 20% of its typical isometric strength</u>, and a <u>full thickness tear as a muscle at 0% of its typical isometric strength</u> (i.e., unable to transmit forces). Note that if a multiple has multiple lines of action/regions, then you would want to adjust the isometric strength of all the lines of action/regions.

- Case 1: No rotator cuff tear
- Case 2: Full thickness tear of the supraspinatus
- Case 3: Full thickness tear of the supraspinatus and large thickness tear of the infraspinatus

1. Watch the following videos:

5_editing_saving_models
6_exporting_plot_data; for Mac users, you will <u>also</u> need to watch 6supp_opening_mot_file

2. Create (and save) 2 different shoulder models representing Cases 2 and 3 listed above. Note: although you can have multiple models open simultaneously in OpenSim, I <u>strongly recommend</u> for you to have only one model open in the software at a time to avoid inadvertently plotting and outputting data from a different model than the one you are targeting.

3. Working with the base model (Case 1), quantify the sum of the moments that can be generated by all the "abductors" you identified in Part 1 of this assignment <u>throughout the frontal plane abduction motion</u>. Even if a muscle was identified as an "abductor" for only parts of the motion, include it in the total abduction moment. Repeat with the sum of the moments of the "adductors", "internal rotators", and "external rotators" that you similarly identified in Part 1 of this assignment. Similarly, if a muscle was identified as an "adductor" or "internal rotator" or "external rotator" for only part of the motion, include it in the sum. As shown in the video, you can export the data from OpenSim by right clicking on a plot and save it as a *filename.mot* file. Make sure that you include the extension ".mot" in the filename. This file can be opened in Excel.

4. Repeat Step 3, but for all the different models representing different severities of rotator cuff injuries (Cases 2-3). Save the data from each model in a separate .mot file.

5. Copy and paste all the data from the 3 different models from Steps 3-4 into a <u>single</u> .xlsx file. It is important to save as a .xlsx file as any calculations or plots within this file will be saved upon closing the file.

6. Plot the total abduction moment generating capacity over the entire movement from all models into a single figure. Your figure should have 3 lines (representing each case), with the y-axis being the total abduction moment from all the abductors and the x-axis being time of the movement. Repeat this process for total maximum adduction, internal rotation, and external rotation moment. You should have a total of 4 figures, one for each action.

7. Identify the magnitude of the <u>peak</u> abduction moment during the movement for each case. Repeat for the adduction, internal rotation, and external rotation moments. Be careful with the signs of your moments on whether you should be finding the maximum or minimum. Report the magnitude (i.e., absolute value) of the peak in Table 2 below. Using the magnitude of the peak, calculate the change in moment in absolute and relative terms for Cases 2-3 using Case 1 as the reference (i.e., value 1 in the equations below). Ignore cases 4-6 for now, those will be completed in Part 3 of this assignment):

$$\text{Absolute Change} = Value\ 2 - Value\ 1$$

$$\text{Relative Change} = \frac{Value\ 2 - Value\ 1}{Value\ 1} \times 100\%$$

Table 2: [Insert a relevant and <u>specific</u> table caption here in your report. Remember, your caption should give the reader details on how to interpret <u>all</u> pieces of information in the table and what they mean. Be as detailed as possible!].

Tear	**Abduction**			**Adduction**			**Internal Rotation**			**External Rotation**		
Case	Peak	Abs Δ	Rel Δ	Peak	Abs Δ	Rel Δ	Peak	Abs Δ	Rel Δ	Peak	Abs Δ	Rel Δ
1		N/A	N/A		N/A	N/A		N/A	N/A		N/A	N/A
2												
3												
4												
5												
6												

8. **Question #1 (3 marks)**: Based on your results and your knowledge of shoulder function, what do you think are the consequences of a posterior-superior rotator cuff tear on an individual's ability to move their arm in the frontal plane? Please use your results to support your argument. Are there any other functions of the rotator cuff muscles that are important for healthy shoulder movement that we did not consider here that may also contribute to impaired frontal plane movement with tears afflicting those muscles?

Part 3:

Your **third goal** is to simulate the potential effectiveness of tendon transfer options for an irreparable posterior-superior rotator cuff tear. Tendon transfer surgeries is one solution for scenarios when damage to the afflicted rotator cuff tendons is not repairable (involves multiple tendons, retracted, and have advanced fatty infiltration) and aims to replace the rotator cuff actions through re-routing the pathways of other healthy musculotendons, thereby restoring shoulder function. We will consider three potential options of tendon transfers for an individual with a full thickness tear of the supraspinatus and a large thickness tear of the infraspinatus):

- Case 4: Case 3 (from above) with an isolated latissimus dorsi tendon transfer
- Case 5: Case 3 (from above) with an isolated teres major tendon transfer
- Case 6: Case 3 (from above) with an isolated lower trapezius tendon transfer

To learn more about tendon transfers for massive, irreparable posterior-superior rotator cuff tears (descriptions and pictures), see the posterior-superior tendon transfer sections in the following reviews:

Axe, J. M. (2016). Tendon transfers for irreparable rotator cuff tears: an update. *EFORT Open Reviews*, 1:18-24.

Clark, N. J., & Elhassan, B. T. (2018). The of tendon transfers for irreparable rotator cuff tears. *Current Reviews in Musculoskeletal Medicine*, 11(1):141-149.

1. Watch the following video:
7_transfer_model

2. Open model *ThoracoscapularShoulderModelSubject_Transfer.osim* into OpenSim. Note that you *may* have to load the user plugin prior to being able to open the model. This model has additional “transfer muscles” implemented that represent the pathways of the latissimus dorsi, teres major, and lower trapezius that have had their pathway altered (“transferred”) to replace the function of the supraspinatus and infraspinatus muscles. Note that the base version of these muscles is still included in the model for you to visualize the difference in muscle pathways. For example, there is a *TeresMajor*, which represents its typical pathway, and a *TeresMajor_transfer*, which is the transferred pathway.

3. **Question #2 (1 mark)**: Where is the new attachment location of the transferred muscles in the model? (Hint: I am looking for a very specific answer in relation to the musculoskeletal anatomy of a healthy shoulder).

4. **Question #3 (2 Marks)**: Have any of the musculotendon model parameters changed for the transferred muscles? If so, which one? Why might I have made this change? (Hint: see the Axe (2016) and/or Clark & Elhassan (2018) reviews cited above).

5. **Question #4 (1 mark)**: Based on your experience from Part 1 with identifying the functional roles/actions of muscles, how have the functions of each of the targeted muscles at the glenohumeral joint been altered with their transferred pathways?

6. Adjust the strength of the infraspinatus and supraspinatus muscles in this transfer model to match Case 3 (full thickness tear of the supraspinatus and large thickness tear of the infraspinatus) from the previous section. Save this as a new model to avoid re-writing the base transfer model. Load the frontal plane abduction motion to this model.

7. Like what you did in Part 2, quantify the sum of the moments <u>throughout the frontal plane abduction motion</u> generated by all the "abductors", "adductors", "internal rotators", and "external rotators" of the humerus in the newest model for Case 4 (replicating a latissimus dorsi tendon transfer for an individual with a full thickness tear of the supraspinatus and a large thickness tear of the infraspinatus). Make sure to not use the base latissimus muscle (*LatissimusDorsi_S*, *LatissimusDorsi_M*, *LatissimusDorsi_I*) but rather the transferred muscle so that you are not double counting for the same muscle. For Case 4, you are considering a latissimus dorsi transfer <u>in isolation</u>, so do not use the transfer versions of the other two muscle options (teres major and lower trapezius) but rather their original pathways. To be specific:
    - Use the following muscles (in addition to the other muscles in the model)
        - *LatissimusDorsi_S_Transfer*
        - *LatissimusDorsi_M_Transfer*
        - *LatissimusDorsi_I_Transfer*
        - *TeresMajor*
        - *TrapeziusScapula_I*
    - Do not use the following muscles
        - *LatissimusDorsi_S*
        - *LatissimusDorsi_M*
        - *LatissimusDorsi_I*
        - *TeresMajor_Transfer*
        - *TrapeziusScapula_I_Transfer*

    <u>IMPORTANT NOTE</u>: For the transferred muscle, only consider and add its contribution to abduction and external rotation (and do not account for it when quantifying the adduction and internal rotation moments) even if it may have some function for adduction and/or internal rotation.

8. Repeat Step 7 for Case 5 (teres major tendon transfer) and Case 6 (lower trapezius tendon transfer). Again, consider these transfers in isolation. For example, when simulating the teres major tendon transfer, use the base version of the latissimus dorsi and lower trapezius with their original pathways and not the transferred versions of them. The same "IMPORTANT NOTE" mentioned in Step 7 applies here

9. From the figures you created in Part 2 (Step 6) of the assignment, add the results from Cases 4-6. You should have in total 4 figures with 6 lines (representing each case) in each figure.

10. Identify the magnitude of the peak moment for each of the new Cases (4-6) and calculate the loss in peak moments in absolute and relative terms, again using Case 1 as the reference. Report this data in the remaining sections of Table 2 from the Part 2 of this assignment.

11. **Question #5 (4 Marks)**: The goal of the tendon transfer surgery is to restore the lost function by the damaged rotator cuff muscles. Based on your simulated surgeries, which muscle (latissimus dorsi, teres major, or lower trapezius) would you recommend that best achieves this goal while considering the potential trade-offs/drawbacks? Please use your results (and consider <u>all</u> your data) to support your argument.

12. **Question #6 (12 Marks)**: How does your modelling-based argument from Question #5 compare to the findings by prominent researchers/clinicians from the Mayo Clinic in the study by Hartzler et al. (2012) cited below? Do you have similar or different recommendations to Hartzler et al. (2012)? If different, what might explain the differences (be specific!)? What are the pros and cons of the approach you undertook in this assignment compared to the study by Hartzler et al. (2012)? Are there any biomechanical or neurophysiological aspects that were unaccounted for in our analysis as well as the cited study that would be important to consider for evaluating the viability of tendon transfer options? You may find helpful ideas from our lecture notes of weeks 6 and 7, including Erin Lee's guest lecture.
    - Hartzler, R. U., Barlow, J. D., An, K.N., Elhassan, B. T. (2012). Biomechanical effectiveness of different types of tendon transfers to the shoulder for external rotation. *Journal of Shoulder and Elbow Surgery*, 21(10):1370-1376.

Deliverables:

A written report (.pdf format) to be submitted directly on Avenue with the following included**:**

1. Table 1 from Part 1.
    - Functional roles of the shoulder muscles at the glenohumeral joint throughout the frontal plane abduction movement analyzed.
2. Table 2 from Parts 2/3.
    - Peak moment generating capacity in 4 directions during a frontal plane abduction movement for different simulated cases (healthy, rotator cuff injury, tendon transfer) and absolute/relative changes in peak moments.
3. Figures 1-4 from Part 2/3 of this assignment.
    - Sum of moments generated by all abductors, adductors, internal rotators, and external rotators throughout frontal plane abduction over time.
    - Each direction should be a separate figure.
    - All cases (1-6) should be plotted in each figure (total of 6 lines per figure).
4. Answers to the following questions from Parts 2/3 of the assignment
    - **Question #1**: Based on your results and your knowledge of shoulder function, what do you think are the consequences of a posterior-superior rotator cuff tear on an individual's ability to move their arm in the frontal plane? Please use your results to support your argument. Are there any other functions of the rotator cuff muscles that are important for healthy shoulder movement that we did not consider here that may also contribute to impaired frontal plane movement with tears afflicting those muscles?
    - **Question #2**: Where is the new attachment location of the transferred muscles in the transfer model? (Hint: I am looking for a very specific answer in relation to the musculoskeletal anatomy of a healthy shoulder).
    - **Question #3**: Have any of the musculotendon model parameters changed for the transferred muscles? If so, which one? Why might I have made this change? (Hint: see the Axe (2016) and/or Clark & Elhassan (2018) reviews cited)
    - **Question #4**: Based on your experience from Part 1 with identifying the functional roles/actions of muscles, how have the functions of each of the targeted muscles at the glenohumeral joint been altered with their transferred pathways?
    - **Question #5**: The goal of the tendon transfer surgery is to restore lost function by the damaged rotator cuff muscles. Based on your simulated surgeries, which muscle (latissimus dorsi, teres major, or lower trapezius) would you recommend that best achieves this goal while considering the potential drawbacks? Please use your results (and consider <u>all</u> your data) to support your argument.
    - **Question #6**: How does your modelling-based argument from Question #5 compare to the findings by prominent researchers/clinicians from the Mayo Clinic in the study by Hartzler et al. (2012) cited in Part 3? Do you have similar or different recommendations to Hartzler et al. (2012)? If different, what might explain the differences (be specific!)? What are the pros and cons of the approach you undertook in this assignment compared to the study by Hartzler et al. (2012)? Are there any biomechanical or neurophysiological aspects that were unaccounted for in our analysis as well as the cited study that would be important to consider for evaluating the viability of tendon transfer options? You may find helpful ideas from our lecture notes of weeks 6 and 7, including Erin Lee's guest lecture.

Grading Criteria:

- 40 marks
  - 4 marks – Table 1
    - 1 mark for the correct list of muscles for each of abduction, adduction, internal rotation, and external rotation. Part marks considered based on number of errors.
    - Marks will be deducted if an appropriate and/or specific table caption is not included.
  - 5 marks – Table 2
    - 1 mark for each of the directions (abduction, adduction, internal rotation, external rotation) correctly calculated. Part marks considered based on number of errors.
    - 1 mark for an appropriate and specific table caption.
  - 8 marks – Figures 1-4
    - 2 marks for each figure
    - The quality of your figures will be taken into consider while grading (i.e., appropriate font usage, axis labels, scales, legend, etc.)
  - 23 marks – Questions
    - 3 marks – Question 1
      - 2 marks for correctly identifying and justifying (based on your results) the consequences of rotator cuff tears
      - 1 mark for identifying functions of the supraspinatus and infraspinatus that were not evaluated
    - 1 mark – Question 2
      - 1 mark for correctly identifying the location
    - 2 marks – Question 3
      - 1 mark for correctly identifying the musculotendon parameter
      - 1 mark for justifying why this change was made
    - 1 mark – Question 4
      - 1 mark for correctly identifying the changes in glenohumeral joint functional roles for all muscles
    - 4 marks – Question 5
      - 4 marks – this question will be marked as a whole based on your thought process and the strength of your argument, as well as using your results to rationalize your answer
    - 12 marks – Question 6
      - 2 marks for explaining similarities/differences in recommendations
      - 4 marks for explaining why there may or may not have been differences in recommendations (be specific!)
      - 3 marks for identifying advantages and disadvantages of your approach versus the cited study
      - 3 marks for identifying and explaining aspects unaccounted for in the model and your analysis