Muscle Mechanics[[1]](#footnote-1)

# I. Objective

The force-producing properties of muscle are complex, highly nonlinear, and can have substantial effects on movement (see McMahon, 1984 for a review). For simplicity, lumped-parameter, dimensionless muscle models that are capable of representing a variety of muscles with different architectures are commonly used in the dynamic simulation of movement (Zajac, 1989). In this exercise, you will explore the differential equations that describe muscle activation and muscle–tendon contraction dynamics when using a Hill-type muscle model. You will use OpenSim to implement a simple muscle–tendon model and conduct simulations to investigate how various model parameters affect the dynamic response of the actuator.

By working through this lab, you will:

* Become familiar with the differential equations describing muscle activation and muscle–tendon contraction dynamics.
* Learn how to model and simulate muscle–tendon dynamics using OpenSim.
* Become comfortable with modifying existing code that models muscle activation and muscle–tendon mechanics.
* Explore the effect of various model parameters and simulation conditions on the dynamic response of muscle.

# II. Acknowledgements

The original lab was designed by Jeff Reinbolt, B.J. Fregly, Kate Saul, Darryl Thelen, Silvia Blemker, Clay Anderson, and Scott Delp. The lab was refined by Hoa Hoang and Daniel Jacobs.

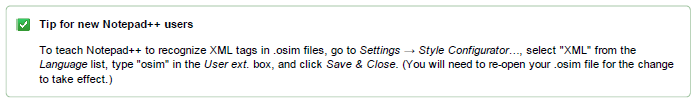
# III. Model

The model in this exercise consists of a cube with a single translational degree of freedom along the Z-axis. A Tug\_of\_War model has been included in the OpenSim distribution (Models/Tug\_of\_War/) that uses two Thelen 2003 Muscles to move the cube. The muscles are arranged to pull on opposite sides of the cube. The cube has a mass of 20 kg and sides of length 0.1 m, and the distance between the fixed ground supports is 0.7 m. Thus, each muscle–tendon actuator is 0.3 m long when the block is centered.

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# IV. Explore and edit OpenSim model, storage, and controls files

For the following exercise, it is recommended that you have a program capable of recognizing XML tags and folding code (e.g., Notepad++).

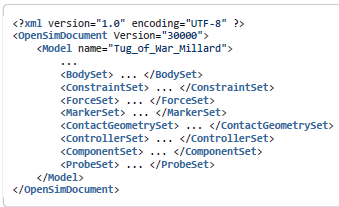


The necessary files are located in the "Models/Tug\_of\_War" folder of the OpenSim distribution. Locate the model *'Tug\_of\_War.osim'*, controls file *'Tug\_of\_War \_controls.xml'* , and initial states file *'Tug\_of\_War\_ initial\_states.sto'* and copy them into your working directory. Copy the model and save it with the filename Tug\_of\_War\_Iso.osim.

An OpenSim model is created using a series of XML elements. An XML element consists of a start tag, a value, and an end tag. The value between the start and end tags can be a string, a number, or another XML element.

Open the model file (Tug\_of\_War\_ Iso.osim) in your favorite text editor. At the top of the file, you will find a block that indicates the presence of XML content, then an XML element called OpenSimDocument. Within the OpenSimDocument element is a Model element consisting of several model components. You may recognize the model components as categories shown in the Navigator Pane of the OpenSim GUI.

# Click to Expand: Basic Model XML



Create a set of files for a single muscle simulation as follows:

* In the model file (Tug\_of\_War\_Iso.osim), change the Model name to "Tug\_of\_War\_ Iso". Expand the ForceSet element and remove the Thelen2003Muscle element named "muscle2". Expand the Thelen2003Muscle element named "muscle1" and set its default\_activation property to 0.01.
* Create a copy of the controls file (Tug\_of\_War\_controls.xml) and name it "Iso\_controls.xml".
* In the new controls file (Iso\_controls.xml), delete the ControlLinear element named "muscle2.excitation".
* Create a copy of the initial states storage file (Tug\_of\_War\_ initial\_states.sto) and name it "Iso\_initial\_states.sto".
* In the new storage file (Iso\_initial\_states.sto), delete the columns for "muscle2.activation" and "muscle2.fiber\_length".
* Update the number of columns (nColumns) to 5.

Open the new Isometric model in the OpenSim GUI.

Configure the Forward Dynamics Tool as follows:

* In the Input pane, load the controls file (Iso\_controls.xml) and the initial states file (Iso\_initial\_states.sto) and check "Solve for equilibrium for actuator states".
* Open the Excitation Editor and set the muscle1 excitation to the maximum value of 1.0 for the entire time range. Save the file and close the editor.
* Set the time range to between 0 and 0.5 seconds.
* Append "\FWD\_Isometric" to the output directory.
* Open the Analyses tab and add a ForceReporter analysis.
* Save the Forward Dynamics Tool settings to "Setup\_FWD\_isometric.xml".

# V. Examine the effect of tendon-to-fiber length ratio on isometric contraction simulations

Zajac (1989) showed that the ratio between the tendon slack length and the optimal muscle fiber length can have a substantial effect on the mechanical response of a muscle–tendon actuator. In this section, you will vary this ratio and examine the mechanical response of the muscle–tendon actuator during isometric contractions.

Set the block\_tz coordinate to zero and lock the coordinate in the GUI.

Run a forward dynamic simulation of isometric contraction using tendon-to-fiber length ratios of 0.5, 1.0, 2.0, 4.0, and 8.0. For each ratio, ensure the sum of the tendon slack length and the optimal fiber length is constant. Perform the following tasks for each tendon-to-fiber length ratio:

* In the OpenSim GUI, open the ForceSet element in the Navigator. Expand the Muscles category and then select muscle1 to display its information in the Properties pane.
* Modify the "optimal\_fiber\_length" and "tendon\_slack\_length" properties according to the tendon-to-fiber length ratio.
* For the given ratio, create a new initial states storage file where the initial fiber length is set to the optimal fiber length value and the initial activation is 0.01.
* Run a forward dynamic simulation using the settings file you created in the previous section. Ensure that the controls file maximally excites the muscle for the entire simulation, and that the initial states file correctly sets the initial activation and fiber length.
* Plot the muscle force vs. time for each tendon-to-fiber length ratio and analyze the resulting simulations.

# VI. Examine the effect of tendon-to-fiber length ratio on isokinetic contraction simulations

In this section, you will evaluate the effect of the ratio between the tendon slack length and the optimal fiber length on an isokinetic (i.e., constant-velocity) contraction. The motion you will be using to calculate muscle forces is 1 second in duration and moves the cube at a speed of 0.1 m/s.

Copy the motion file "Tug\_of\_War\_ConstantVelocity.sto" from the "Models/Tug\_of\_War" folder into your working directory. Unlock the block\_tz coordinate in the OpenSim GUI. Load the motion into the OpenSim GUI and play the animation.

For the same set of tendon-to-fiber length ratios (0.5, 1.0, 2.0, 4.0, and 8.0), run a forward simulation of isokinetic contraction. For each ratio, ensure the sum of the tendon slack length and the optimal fiber length is constant. Use the controls and initial states files from the previous section. To calculate the muscle forces, you will use the Analyze Tool to recreate the force profiles given the known information. The activation, fiber length, and fiber shortening/lengthening velocity are needed to calculate the muscle force using a Hill-TypeMuscle model. Given the excitation history, the activation history can be determined using the first-order activation dynamic model. The loaded motion for the block kinematics is used to calculate the muscle fiber length and velocity at each time step. The Analyze Tool uses this information to calculate the muscle force applied to the block.

For more background on the Analyze Tool, see the Analyses page in the User Guide.

Perform the following tasks for each tendon-to-fiber length ratio:

* Before you open the Analyze Tool, ensure the "optimal\_fiber\_length" and "tendon\_slack\_length" properties have been set correctly for muscle1. Also, set "default\_activation" to 1.0 for this part of the lab only.
* Open the Analyze Tool.
* In the Input pane, select "Iso\_controls.xml" for the controls file.
* In the Input pane, select Motion and ensure the Loaded Motion is set to the "Tug\_of\_War\_ConstantVelocity" motion.
* Check the box for "Solve for equilibrium for actuator states".
* Set the time range to between 0 and 1 second.
* In the Analyses tab, add a ForceReporter.
* Plot the muscle force of the LeftMuscle vs. time and analyze the resulting simulations.
* Right-click on the plot and select "Export Data...". Save the result file as TendonForceVsMotion\_ratioX.sto, where X is the current tendon-to-fiber length ratio.

# Questions

1. *How many degrees of freedom are in the Tug\_of\_War.osim model? What are they?*
2. *What are the values of the four primary muscle parameters (maximum isometric force, optimal fiber length, tendon slack length, and pennation angle at optimal fiber length) for each muscle?*
3. *Which XML elements in the controls file (Tug\_of\_War\_controls.xml) describe the excitation signals?*
4. *Isometric Simulations: Plot the muscle force vs. time for all five tendon-to-fiber length ratios on a single set of axes.*
5. *Isometric Simulations: Describe any differences you observe between the curves in terms of the rate of force development and the steady-state force achieved.*
6. *Isometric Simulations: Using what you know about muscle mechanics and dynamics, explain the difference in muscle force response with respect to changes in tendon-to-fiber length ratio.*
7. *Isokinetic Simulations: Plot the tendon force vs. position for all five tendon-to-fiber length ratios on a single set of axes.*
8. *Isokinetic Simulations: Describe any differences you observe between the curves in terms of the rate of force development and the steady-state force achieved.*
9. *Isokinetic Simulations: Using what you know about muscle mechanics and dynamics, explain the difference in muscle force response with respect to changes in tendon-to-fiber length ratio.*

# References

1. Anderson, F.C. and Pandy, M.G. (1999). A dynamic optimization solution for vertical jumping in three dimensions. Computer Methods in Biomechanics and Biomedical Engineering, 2(3):201–231.
2. Hatze, H. (1976). The complete optimization of a human motion. Mathematical Biosciences, 28(1–2):99–135.
3. McMahon, T.A. (1984). Muscles, Reflexes, and Locomotion. Princeton University Press, Princeton, New Jersey.
4. Millard, M., Uchida, T., Seth, A., Delp, S.L. (2013). Flexing computational muscle: modeling and simulation of musculotendon dynamics. ASME Journal of Biomechanical Engineering, 135(2):021005.
5. Schutte, L.M. (1993). Using Musculoskeletal Models to Explore Strategies for Improving Performance in Electrical Stimulation-Induced Leg Cycle Ergometry. PhD Dissertation, Mechanical Engineering Department, Stanford University.
6. Thelen, D.G. (2003). Adjustment of muscle mechanics model parameters to simulate dynamic contractions in older adults. ASME Journal of Biomechanical Engineering, 125(1):70–77.
7. Winters, J.M. (1990). Hill-based muscle models: a systems engineering perspective, in Multiple Muscle Systems: Biomechanics and Movement Organization, edited by Winters, J.M. and Woo, S.L., Springer-Verlag, New York.
8. Zajac, F.E. (1989). Muscle and tendon: properties, models, scaling, and application to biomechanics and motor control. Critical Reviews in Biomedical Enginering, 17(4):359–411.

# Deliverables

Answer all questions posed in the tutorial and turn in your report electronically (as a .docx format) using Blackboard. Restate each question, followed by your answer. Be sure to include plots and/or figures to support your answers. For example, if you answer a question with ‘the knee flexion moment arm of the hamstrings decreased with knee flexion angle’, be sure to include a plot to support your statement. The report will be graded as follows:

|  |  |
| --- | --- |
| **Question** | **Points Possible** |
| 1. How many degrees of freedom are in the Tug\_of\_War.osim model (1pt)? What are they (1pt)? | 2 |
| 1. What are the values of the four primary muscle parameters (maximum isometric force, optimal fiber length, tendon slack length, and pennation angle at optimal fiber length) for each muscle? (4pts for each muscle) | 8 |
| 1. Which XML elements in the controls file (Tug\_of\_War\_controls.xml) describe the excitation signals? (1pt) | 1 |
| 1. Isometric Simulations: Plot the muscle force vs. time for all five tendon-to-fiber length ratios on a single set of axes. (5pts) | 5 |
| 1. Isometric Simulations: Describe any differences you observe between the curves in terms of the rate of force development and the steady-state force achieved. (1pt) | 1 |
| 1. Isometric Simulations: Using what you know about muscle mechanics and dynamics, explain the difference in muscle force response with respect to changes in tendon-to-fiber length ratio. (1pt) | 1 |
| 1. Isokinetic Simulations: Plot the tendon force vs. position for all five tendon-to-fiber length ratios on a single set of axes. (5pts) | 5 |
| 1. Isokinetic Simulations: Describe any differences you observe between the curves in terms of the rate of force development and the steady-state force achieved. (1pt) | 1 |
| 1. Isokinetic Simulations: Using what you know about muscle mechanics and dynamics, explain the difference in muscle force response with respect to changes in tendon-to-fiber length ratio. (1pt) | 1 |
| **Total** | **25** |

1. This lab adapted from <http://simtk-confluence.stanford.edu:8080/display/OpenSim/Pulling+Out+the+Stops%3A+Designing+a+Muscle+for+a+Tug-of-War+Competition> [↑](#footnote-ref-1)