

# ME/BIOE 481: ASSIGNMENT 3 - Muscle Tug-of-War

Updated: March 22, 2021 (MEK)

## 1 Critical info

- Due date: March 29, 2021 - 11:59PM (US Central standard time)
- You may work in pairs or triplets. Instructions are below.
- Requires OpenSim 4.1 software (<https://opensim.stanford.edu>) Base model files for this exercise are included in the OpenSim 4.1 distribution are found on the course web page (link to box folder).

## 2 Objective

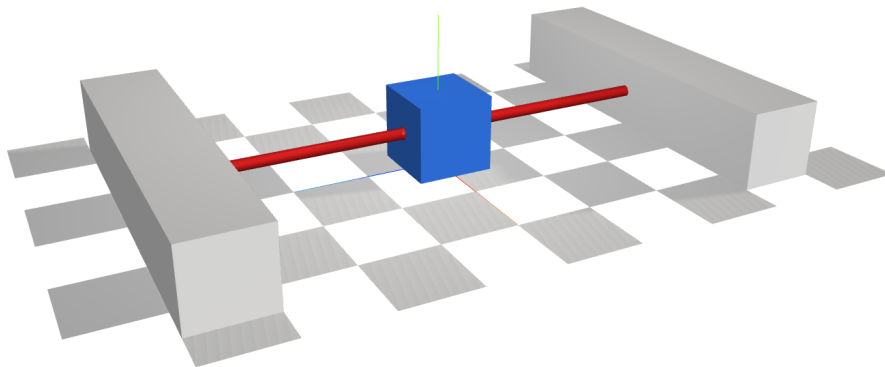
The force-producing properties of muscle are complex, highly nonlinear, and can have substantial effects on movement (see McMahon, 1984 for a review). For simplicity, lumped-parameter, dimensionless muscle models that are capable of representing a variety of muscles with different architectures are commonly 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. The lab will conclude with a Virtual Muscle Tug-of-War in which you will design an optimal muscle and compete against other user-generated muscles. May the best muscle win!

By working through this lab, you will:

1. Become familiar with muscle activation and muscle–tendon contraction dynamics.
2. Learn how to model and simulate muscle–tendon dynamics using OpenSim.
3. Become comfortable with modifying existing code that models muscle activation and muscle–tendon mechanics.
4. Explore the effect of various model parameters and simulation conditions on the dynamic response of muscle.
5. Design your own optimal muscle–tendon actuator to compete in a virtual muscle tug-of-war.

## 3 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. In this exercise, we will use two Millard 2012 Muscles instead of the Thelen muscles. 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 (Fig 1). Thus, each muscle–tendon actuator is 0.3 m long when the block is centered.



**Figure 1:** View of tug of war model

## 4 Background

### 4.1 Determinants of muscle force

Musculotendon actuators consist of an active contractile element, a passive elastic element, and an elastic tendon. The maximum active force a muscle can develop varies nonlinearly with its length, represented by the active-force-length curve, peaking at a force of  $f_{M,o}$  at a length of  $l_{M,o}$ . Note that a tilde is used to denote forces, velocities, muscle lengths, and tendon lengths that are normalized, respectively. During non-isometric contractions, the force developed by muscle varies nonlinearly with its rate of lengthening, which is represented by the force-velocity curve. Force is also developed when muscle is stretched beyond a threshold length, regardless of whether the muscle is activated, which is represented by the passive-force-length curve. Total muscle force is computed using these curves simultaneously and can be visualized as a surface:

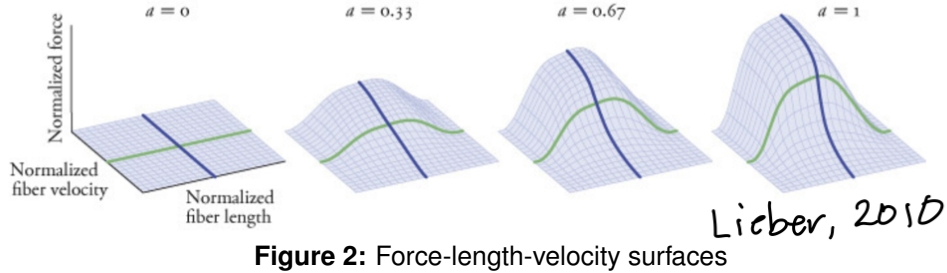


Figure 2: Force-length-velocity surfaces

The maximum height of the surface is governed by  $a$ , muscle activation, which ranges from  $a_{min} = 0$  to  $a_{max} = 1$ . Mathematically these are described as:

$$f^M = f_o^M \left( a f^L(\tilde{\ell}^M) f^V(\tilde{v}^M) + f^{PE}(\tilde{\ell}^M) \right)$$

Muscle attaches to bone through tendon. Since a long tendon may stretch appreciably beyond its slack length ( $l_{t,s}$ ) when under tension, tendon is modeled as a nonlinear elastic element developing force according to the tendon-force-length curve. Muscle fibers attach to tendon at a pennation angle ( $\alpha$ ), scaling the force they transmit to the tendon. If the tendon is assumed to be elastic and the mass of the muscle is assumed to be negligible, then the muscle-tendon force equilibrium equation (i.e.,  $f_{Mcos} - f_T = 0$ ) takes the following form:

$$f_o^M \left( a f^L(\tilde{\ell}^M) f^V(\tilde{v}^M) + f^{PE}(\tilde{\ell}^M) \right) \cos \alpha - f_o^M f^T(\tilde{\ell}^T) = 0 \quad (1)$$

### 4.2 Millard 2012 Muscle Model

Millard and colleagues developed default force curves for the musculotendon model that have been fit to experimental data (Millard et al., 2013). These curves can be adjusted to model muscle and tendon whose characteristics deviate from these default patterns.

In a forward-dynamic simulation, the force generated by a musculotendon actuator is calculated from the length ( $l_m$ ), velocity ( $v_m$ ), and activation ( $a$ ) of the muscle. The length  $l_m$  is obtained by integrating the velocity  $v_m$ , which is obtained by solving Eq. (1) for the normalized muscle velocity, thereby providing an ordinary differential equation (see Zajac, 1989):

$$\tilde{v}^M = f_{inv}^V \left( \frac{f^T(\tilde{\ell}^T) / \cos \alpha - f^{PE}(\tilde{\ell}^M)}{a f^L(\tilde{\ell}^M)} \right) \quad (2)$$

where  $f_{inv}^V$  is the inverse of the force-velocity curve. Eq. (1) is devoid of numerical singularities, Eq. (2) has four:

- as  $\alpha \rightarrow 90$  deg
- as  $a \rightarrow 0$
- as  $f^L \rightarrow 0$
- as  $\partial f^V(\tilde{v}^M) / \partial \tilde{v}^M \rightarrow 0$

Since these conditions are often encountered during a simulation, the quantities causing singularities in Eq. (2) are altered so that the singularities are approached but never reached. Without modifying the formulation of the equilibrium model, the muscle is able to reach unrealistically short lengths (Thelen, 2003) and cannot be simulated when fully deactivated. A unilateral constraint on muscle length is imposed to prevent the muscle from becoming unrealistically short.

### 4.3 Activation Dynamics

A muscle can neither generate force nor relax instantaneously. The development of force is a complex sequence of events that begins with the firing of motor units and culminates in the formation of actin–myosin cross-bridges within the myofibrils of the muscle. When the motor units of a muscle depolarize, action potentials are elicited in the fibers of the muscle and cause calcium ions to be released from the sarcoplasmic reticulum. The increase in calcium ion concentrations then initiates the cross-bridge formation between the actin and myosin filaments. In isolated muscle twitch experiments, the delay between a motor unit action potential and the development of peak force has been observed to vary from as little as 5 milliseconds for fast ocular muscles to as much as 40 or 50 milliseconds for muscles comprised of higher percentages of slow-twitch fibers. The relaxation of muscle depends on the re-uptake of calcium ions into the sarcoplasmic reticulum. This re-uptake is a slower process than the calcium ion release, so the time required for muscle force to fall can be considerably longer than the time for it to develop.

The activation dynamics of muscle can be modeled with a first-order differential equation. This equation relates the rate of change of muscle activation (i.e., the concentration of calcium ions within the muscle) to the muscle excitation (i.e., the firing of motor units):

$$\frac{da}{dt} = \frac{u - a}{\tau(a, u)} \quad (1)$$

where  $u$  and  $a$  are the excitation and activation signals, respectively. In the model, activation is allowed to vary continuously between 0 (no contraction) and 1 (full contraction). In the body, the activation of a muscle is a function of the number of motor units recruited and the firing frequency of these motor units. Some models of excitation–contraction coupling distinguish these two control mechanisms (Hatze, 1976), but it is often not computationally feasible to use such models when conducting complex dynamic simulations. In a simulation, the muscle excitation signal is assumed to represent the net effect of both motor neuron recruitment and firing frequency. Like muscle activation, the excitation signal is also allowed to vary continuously between 0 (no excitation) and 1 (full excitation). The activation and deactivation time constants can be assumed to be 10 and 40 ms, respectively (Zajac, 1989; Winters, 1990).

The activation model presented by Thelen (2003) closely follows the activation dynamic model found in Winters (1995 – Eq. 2, line 2 and Eq. 3), where the time derivative of activation ( $da/dt$ ) is equal to the difference between excitation ( $u$ ) and activation ( $a$ ) scaled by a variable time constant ( $\tau(a, u)$ ). The primary difference between the activation model presented by Thelen and the one presented by Winters lies in their expressions for  $\tau(a, u)$ , which differ only in the values of the two coefficients shown in parentheses in Eqs. 2 and 3:

$$\tau(a, u) = \begin{cases} t_{\text{act}} (0.5 + 1.5a) & : u > a & (2) \\ t_{\text{deact}} / (0.5 + 1.5a) & : u \leq a & (3) \end{cases}$$

Note that the model of activation dynamics presented in Eq. 1 does not respect a lower bound for activation. Equilibrium muscle models (commonly used to model muscle in lumped-parameter musculoskeletal simulations) have a singularity in their state equations when activation is zero, making the above activation dynamic model unsuitable for simulations using equilibrium muscle models. Equation 1 can be made to respect a lower bound on activation by first constraining both activation and excitation to remain between the minimum activation level (0.01 by default) and the maximum activation level (1.0 by default).

Acknowledgments: 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, Daniel Jacobs, and Mariana Kersh.

<https://simtk-confluence.stanford.edu:8443/display/OpenSim/Pulling+Out+the+Stops%3A+Designing+a+Muscle+for+a+Tug-of-War+Competition>

## 5 Design Challenge

The competition is a single-elimination tournament between pairs of muscles. Each match is a one-second forward dynamic simulation where each muscle starts with minimal activation ( $a = 0.01$ ). The match is won by the muscle that has moved the block to its side of the arena at the end of the simulation. Your challenge is to specify the muscle–tendon parameters and excitation time history necessary to overcome the other challengers.

### 5.1 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++ on Windows, TextMate on Mac).

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\_Millard\_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.

```
<?xml version="1.0" encoding="UTF-8" ?>
<OpenSimDocument Version="30000">
  <Model name="Tug_of_War_Millard">
    ...
    <BodySet> ... </BodySet>
    <ConstraintSet> ... </ConstraintSet>
    <ForceSet> ... </ForceSet>
    <MarkerSet> ... </MarkerSet>
    <ContactGeometrySet> ... </ContactGeometrySet>
    <ControllerSet> ... </ControllerSet>
    <ComponentSet> ... </ComponentSet>
    <ProbeSet> ... </ProbeSet>
  </Model>
</OpenSimDocument>
```

### 5.2 Configure the Forward Dynamics Tool as follows:

- Copy the model files from box into your working directory.
- Open the Iso\_initial\_states.sto. Note where the activation and optimal fiber length data are entered.
- Open the 'Tug\_of\_War\_Millard\_Iso.osim' in the OpenSim GUI.
- Open the Forward Dynamics Tool
- 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 (click the button with a pencil and paper next to the Controls field) and set the LeftMuscle excitation to the maximum value of 1.0 for the entire time range (On Mac, use Ctrl + Shift + Left Click to select a control node; multiple nodes can be selected together). Save the file as Iso\_controls1.xml and close the editor. Make sure this file is the one loaded in the gui.

If you cannot edit it within the gui, make a copy of the Iso\_controls.xml file and rename it to Iso\_controls1.xml. Open this file in a text editor and Modify the "value" field after each time point to be a 1.0 for the entire time range. Close the file and load this new file instead of the original one for the controls file in the Forward Dynamics input pane.

- 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".
- Close the Forward Dynamics Tool

### 5.3 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 ( $\ell_{Ts}/\ell_{Mo}$ ) 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 7.0. For each ratio, ensure the sum of the tendon slack length and the optimal fiber length is constant (i.e.,  $\ell_{Ts} + \ell_{Mo} = 0.3\text{m}$ ).

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

- In the OpenSim Navigator GUI, open and expand the Model
- Open the Forces element in the Navigator.
- Expand the Muscles category and then select LeftMuscle 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. Ensure the "default\_activation" property is set to 0.01.
- 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 Section 5.2. Ensure that the controls file maximally excites the muscle for the entire simulation (`Iso_controls1.xml`), and that the initial states file (`Iso_initial_states.sto`) correctly sets the initial activation and fiber length.
- Rename the output directory so that you preserve your results for each ratio.
- Plot the muscle force vs. time for each tendon-to-fiber length ratio and analyze the resulting simulations.

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

Next, 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`" into your working directory. Unlock the `block_tz` coordinate in the OpenSim GUI.

Load the motion into the OpenSim GUI (click on File → Load motion) and play the animation.

For the same set of tendon-to-fiber length ratios (0.5, 1.0, 2.0, 4.0, and 7.0), you will analyze an isokinetic contraction. For each ratio, ensure the sum of the tendon slack length and the optimal fiber length is constant (i.e.,  $\ell_{Ts} + \ell_{Mo} = 0.3\text{m}$ ). Use the controls from the previous section.

To calculate the muscle forces, you will use the Analyze Tool to recreate the force profiles given the known information. As discussed in the introduction to this example, the activation, fiber length, and fiber shortening/lengthening velocity are needed to calculate the muscle force using a Millard2012EquilibriumMuscle 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.

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 the LeftMuscle. Also, set "default\_activation" to 1.0 for this part of the lab only.
- Open the Analyze Tool.
- In the Input pane, select "`Iso_controls1.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.
- Run the Analyze Tool. (You may first save the setup file to speed up running the tool for other ratios.)
- Plot the muscle force of the LeftMuscle vs. time for all tendon-to-fiber length ratios and analyze the resulting simulations.
- If interested, you can save data from the plot to a file. Right-click on the plot and select "Export Data...". Save the result file as TendonForceVsMotion\_Isokinetic.sto.

## 6 Design your best Tug-of-War competitor

You win the competition by getting the center of the block onto your side of the arena at the end of a 1.0-second simulation. For this competition, start with a copy of the original Tug\_of\_War\_Millard.osim model file.

### 6.1 Design variables

The design variables that you can modify to create your competitor are:

- $F_{M,o}$  – Maximum isometric muscle fiber force
- $l_{M,o}$  – Optimal muscle fiber length
- $l_{T,s}$  – Tendon slack length
- $\alpha_o$  – Muscle fiber pennation angle at optimal fiber length
- $u(t)$  – Muscle excitation time history
- $l_{MT}$  – Total length of muscle–tendon actuator
- $V_M$  – Muscle volume
- $Z_{origin}$  – The Z-coordinate of the muscle's attachment point on the ground body

The initial activation will be 0.01 and the initial fiber length will be determined by the equilibrium condition. To match these conditions in your testing, make sure your muscle's default\_activation is 0.01 and enable "Solve for equilibrium for actuator states" when using the ForwardTool.

### 6.2 Constraints

The muscle must obey the following physical relationships and constraints:

- $\sigma_{M,o} = F_{M,o}/A = 35N/cm^2$  – The specific tension of the muscle at its maximum isometric force (from Zajac, 1989).
- $V_M = A * l_{M,o}$
- $l_{MT,initial} = l_{T,s} + l_{M,o}$ , where  $l_{MT,initial}$  is the distance between the origin of the muscle (on the ground) and its attachment point (on the block) at the beginning of the simulation. Note that  $Z_{origin}$  must be set so this constraint is satisfied.
- $V_M \leq 100 \text{ cm}^3$
- $F_{M,o} * v_{M,max} * l_{M,o} \leq 175W$ , where  $v_{M,max}$  is maximum velocity
- $0.15 \text{ m} \leq l_{MT,initial} \leq 0.45\text{m}$ . Note that you can adjust  $Z_{origin}$  to satisfy this constraint.
- $l_{T,s} \geq 0.1\text{m}$
- $0.05\text{m} \leq l_{M,o} \leq 0.2\text{m}$
- $0 \text{ deg} \leq \alpha_o \leq 30\text{deg}$
- $2 \text{ 1/s} \leq v_{M,max} \leq 10 \text{ 1/s}$  (i.e., the max\_contraction\_velocity muscle property must be between 2 and 10)
- $\int u(t)dt \leq 0.5$  (constraint on excitation signal)
- $10\text{ms} \leq \tau_{act} \leq 20\text{ms}$
- $40\text{ms} \leq \tau_{deact} \leq 60\text{ms}$
- $30\text{ms} \leq \tau_{deact} - \tau_{act} \leq 40\text{ms}$

## 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.
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4. 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.
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6. 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.
7. Zajac, F.E. (1989). Muscle and tendon: properties, models, scaling, and application to biomechanics and motor control. *Critical Reviews in Biomedical Engineering*, 17(4):359–411.

# ME/BIOE 481: Dynamic walking model simulation

Updated: March 19, 2021, Mariana E. Kersh

Name: \_\_\_\_\_

Name: \_\_\_\_\_

Name: \_\_\_\_\_

## Critical info

- Due date: March 26, 2021 - 11:59PM (US Central standard time)
- Part 1: 10 points. Plots below
- Part 2: 10 points. Muscle parameters described below.
- Part 3: 2 points. Turn this file into compass and upload model files to box.
- You may work in pairs or triplets.

## PART 1: Analysis of isometric and isokinetic contractions with changing tendon-to-fiber length ratios.

1. How many degrees of freedom are in the Tug\_of\_War\_Millard.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. Isometric: Plot the muscle force vs. time for all five tendon-to-fiber length ratios on a single set of axes.
4. Describe any differences you observe between the curves in terms of the rate of force development and the steady-state force achieved for isometric contractions.
5. Isokinetic: Plot the tendon force vs. time for all five tendon-to-fiber length ratios on a single set of axes.
6. Describe any differences you observe between the curves in terms of the rate of force development and the steady-state force achieved for isokinetic contractions.

## PART 2: Muscle parameters

1. Describe the final muscle design, including a demonstration that each criterion is met (show that it satisfies the constraints listed in 6.2). You must modify the first four parameters, but you may modify more.

### REQUIRED MODIFICATIONS

- $F_{Mo}$  – Maximum isometric muscle fiber force  
Original:            New:
- $\ell_{Mo}$  – Optimal muscle fiber length  
Original:            New:
- $\ell_{Ts}$  – Tendon slack length  
Original:            New:
- $\alpha_0$  – Muscle fiber pennation angle at optimal fiber length  
Original:            New:

### OPTIONAL MODIFICATIONS

- $u(t)$  – Muscle excitation time history  
Original:            New:
- $\ell_{MT}$  – Total length of muscle–tendon actuator  
Original:            New:



- VM – Muscle volume  
Original:            New:
- Zorigin – The Z-coordinate of the muscle's attachment point on the ground body  
Original:            New:

2. (2 pts) Give your muscle a name

- (a) Your muscle name:
- (b) Plot your force vs time for your muscle model (run this for 1 second).
- (c) Upload your forces results file from OpenSim to box - label it with your muscle name. Upload your excitation time history if you choose to change it.