

# Tutorial 1 - Intro to Musculoskeletal Modeling

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The tutorial below is designed for use with OpenSim version 4.0 and later. A version of the tutorial compatible with OpenSim version 3.3 is available [here](#).

## I. Objectives

### Introduction to OpenSim

Musculoskeletal models enable us to study neuromuscular coordination, analyze athletic performance and estimate musculoskeletal loads. OpenSim is an open-source software that allows users to develop, analyze, and visualize models of the musculoskeletal system, and to generate dynamic simulations of movement [1]. In OpenSim, a musculoskeletal model consists of rigid body segments connected by joints. Muscles span these joints and generate forces and motion. Once a musculoskeletal model is created, OpenSim enables users to create custom studies, including investigating the effects of musculoskeletal geometry, joint kinematics, and muscle-tendon properties on the forces and joint moments the muscles can produce. With OpenSim, our goal is to provide a framework that allows the biomechanics community to create, share, and extend a library of models and dynamic simulation tools that can be used to study and quantify human and animal movement.

### Purpose

The purpose of this tutorial is to introduce users to OpenSim by demonstrating the utility of a graphics-based musculoskeletal modeling framework to investigate how muscle-tendon lengths and moment arms depend on limb configuration. In this tutorial, you will:

- Become familiar with OpenSim's graphical user interface (GUI).
- Discover some limitations of musculoskeletal models.
- Explore differences between uni-articular ("1-joint") and bi-articular ("2-joint") muscles.
- Use OpenSim to approach an important clinical problem

### Format

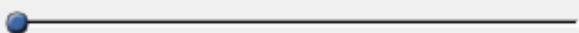


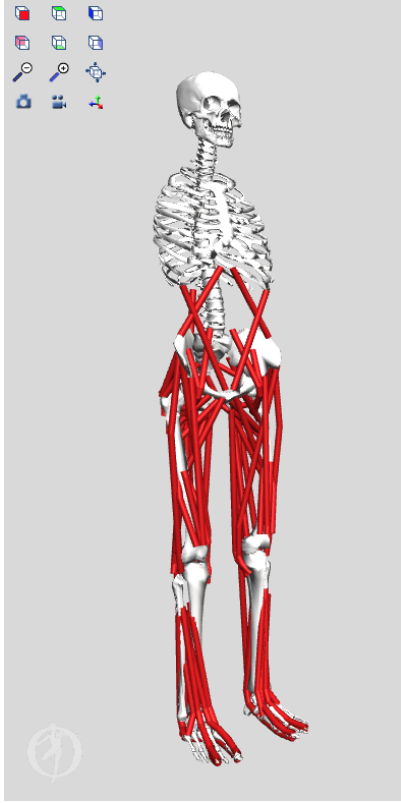
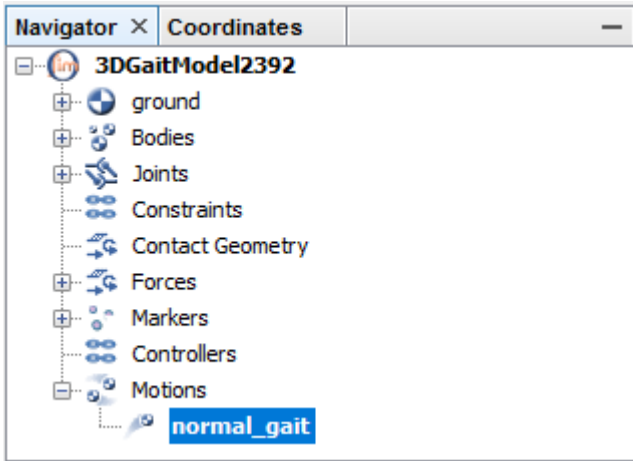
Each section of the tutorial guides you through certain tools within OpenSim's GUI and asks you to answer a few questions. The menu titles and option names you must select and any commands you must type to run OpenSim will appear in bold font. The questions can be answered based on information from OpenSim and basic knowledge of the human musculoskeletal system. As you complete each section of the tutorial, feel free to explore OpenSim and the lower extremity model further on your own. Depending on the amount of exploration you do, this tutorial will take about 1-2 hours to complete.

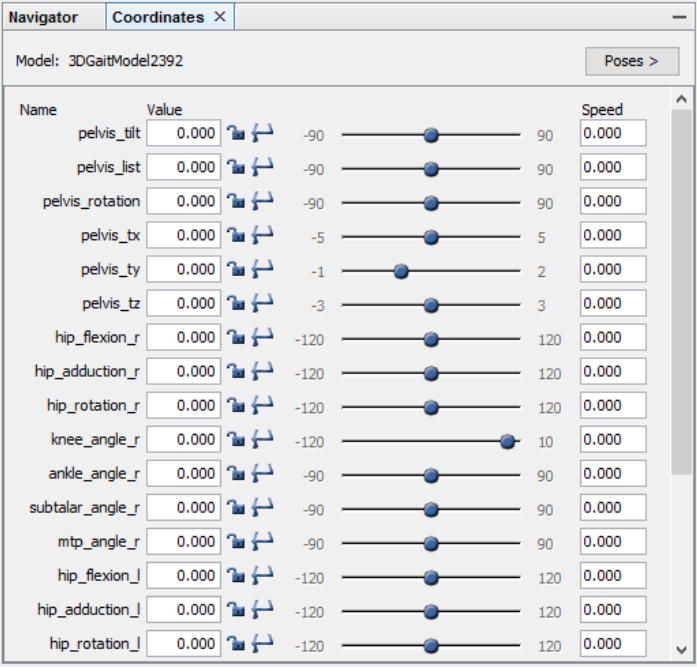
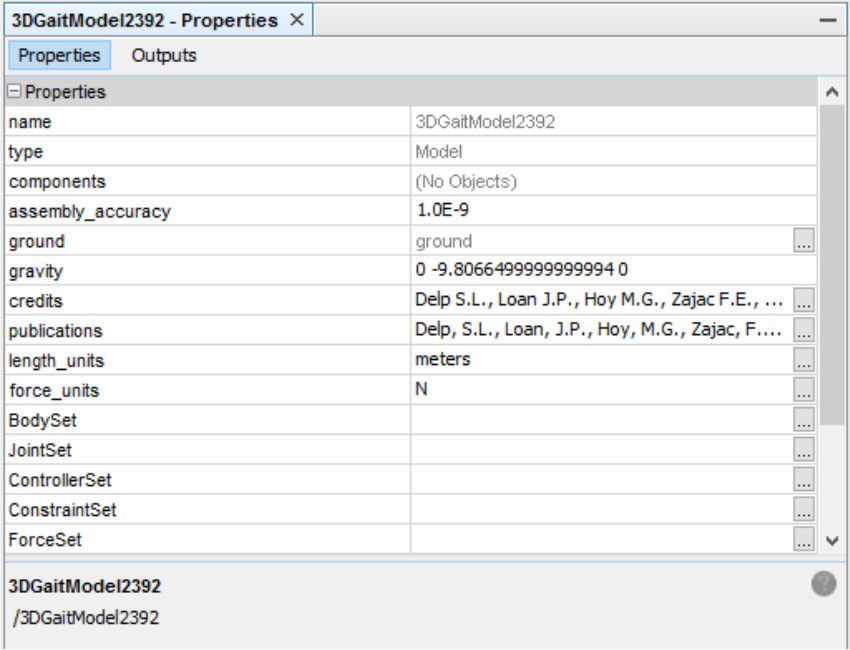
### Introduction to the OpenSim GUI

There are several key components of the OpenSim GUI that will be referred to throughout the tutorial. The table below will introduce you to these GUI components.

*Note: A model is loaded in this example to illustrate the GUI, when you open OpenSim for the first time, there will be no models loaded.*

GUI Components	
Title	Screenshot
Toolbar	

<p><b>Motion Textbox</b></p>	<p><b>Motion:</b> <input type="text" value="normal_gait"/></p>
<p><b>Motion Slider/ Video Controls</b></p>	<p>Time <input type="text" value="0.000"/>  </p> <p>Speed <input type="text" value="1"/> <input type="text" value="0.000"/>  <input type="text" value="1.000"/></p>
<p><b>Visualizer Window</b></p>	
<p><b>Navigator Window</b></p>	

<p><b>Coordinates Window</b></p>																																	
<p><b>Properties Window</b></p>	 <table border="1" data-bbox="493 835 1338 1480"> <thead> <tr> <th>Property</th> <th>Value</th> </tr> </thead> <tbody> <tr> <td>name</td> <td>3DGaitModel2392</td> </tr> <tr> <td>type</td> <td>Model</td> </tr> <tr> <td>components</td> <td>(No Objects)</td> </tr> <tr> <td>assembly_accuracy</td> <td>1.0E-9</td> </tr> <tr> <td>ground</td> <td>ground</td> </tr> <tr> <td>gravity</td> <td>0 -9.8066499999999994 0</td> </tr> <tr> <td>credits</td> <td>Delp S.L., Loan J.P., Hoy M.G., Zajac F.E., ...</td> </tr> <tr> <td>publications</td> <td>Delp, S.L., Loan, J.P., Hoy, M.G., Zajac, F....</td> </tr> <tr> <td>length_units</td> <td>meters</td> </tr> <tr> <td>force_units</td> <td>N</td> </tr> <tr> <td>BodySet</td> <td></td> </tr> <tr> <td>JointSet</td> <td></td> </tr> <tr> <td>ControllerSet</td> <td></td> </tr> <tr> <td>ConstraintSet</td> <td></td> </tr> <tr> <td>ForceSet</td> <td></td> </tr> </tbody> </table>	Property	Value	name	3DGaitModel2392	type	Model	components	(No Objects)	assembly_accuracy	1.0E-9	ground	ground	gravity	0 -9.8066499999999994 0	credits	Delp S.L., Loan J.P., Hoy M.G., Zajac F.E., ...	publications	Delp, S.L., Loan, J.P., Hoy, M.G., Zajac, F....	length_units	meters	force_units	N	BodySet		JointSet		ControllerSet		ConstraintSet		ForceSet	
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For more documentation about the GUI see the User's Guide section on the [Graphical User Interface](#)

## II. Musculoskeletal Model of the Lower Extremity

In this section, you will load a model of the lower extremity [2] into OpenSim and make the model "walk." The model represents an adult subject with an approximate height of 1.8 m and an approximate mass of 75 kg. The model consists of 13 rigid body segments and includes the lines of action of 92 muscles (43 per leg and 6 at the torso).

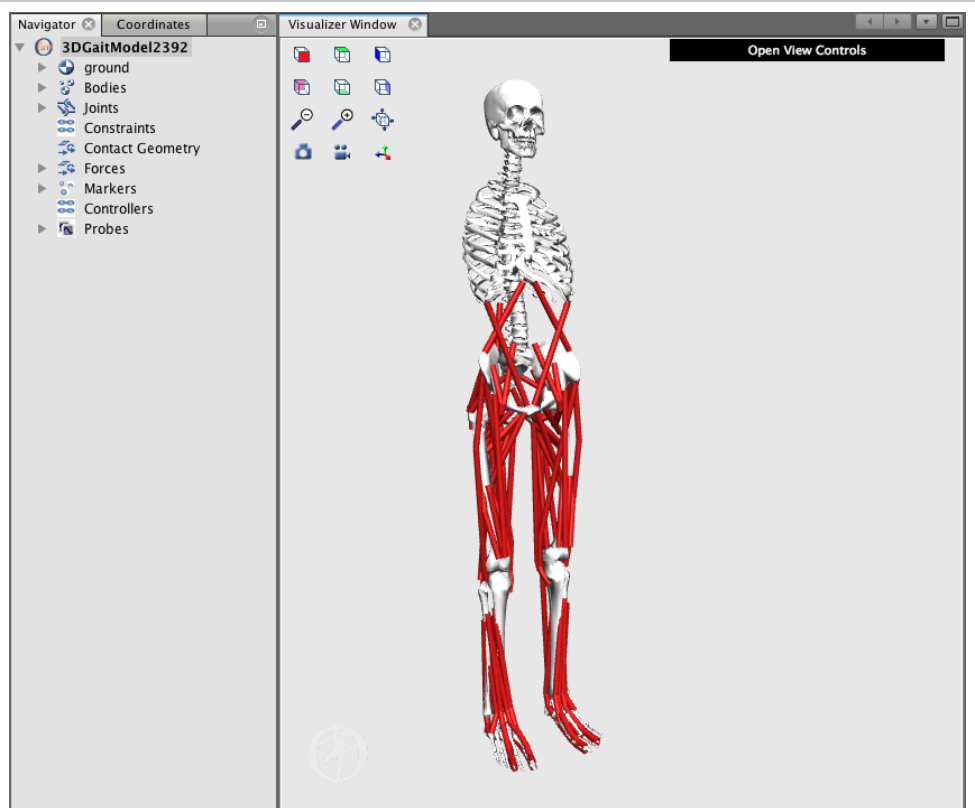
## Loading a Model

The first model you will analyze is gait2392.osim. To load this musculoskeletal model into OpenSim:

- Click the **File** menu and select **Open Model**.
- Find the **Models** folder, which is located in your Documents folder e.g., Documents\OpenSim\4.0 for a PC or, e.g., Documents /OpenSim/4.0 for a Mac.  
*Note: When you first launch OpenSim, the default to install models and scripts files is your Documents folders (you do have the choice to change the folder where you want to install these files). There are several different example models and motions in the Models folder. All of the model and motion files used in the remainder of the tutorial will be located in this Models folder.*
- Open the **Gait2392\_simbody folder**, select the file **gait2392\_simbody.osim**, and click Open.

After loading a model, the Navigator Window will display the model with a given model name, you can change this model name if multiple models are open to distinguish each model. The Navigator window also provides specific information about the bodies, muscles, and joints in the model. If the Navigator window is not visible, click the **Window** menu and select **Navigator**. Use the buttons to the left of the Navigator to expand or collapse the heading.

*Note: If already opened, you can also view the Navigator window by clicking its title bar.*




## Viewing a Model

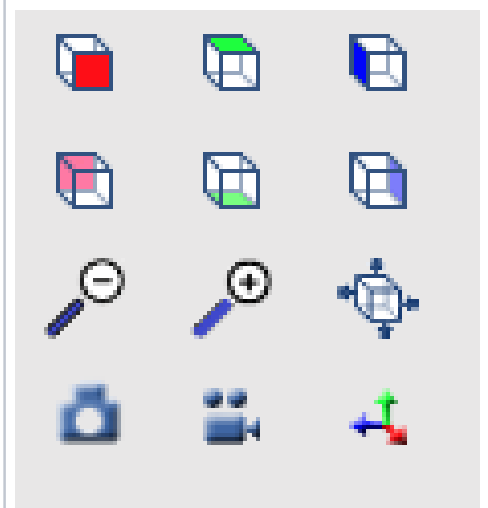
OpenSim allows you to orient the model using your mouse.

Camera Action	Windows	Mac
<i>Rotate</i>	<b>left-click and hold</b> (PC or mouse)	<b>single-finger click and hold</b> (Mac trackpad)
<i>Translate</i>	<b>right-click and hold</b> (PC or mouse)	<b>two-finger click and hold</b> (Mac trackpad)
<i>Zoom</i>	<b>scroll up or down</b> (PC or mouse)	<b>pinch or expand</b> (Mac trackpad).

In addition to your mouse, there are six orienting icons located along the right side of the View window.

- To change the camera to view from the -X direction, click the  icon.
- Similarly, click on the other icons to view from the other principal directions.
- Double click on a body to center it on the screen.

Before continuing, click the  icon to reset the visualizer view.



## Model Coordinates

The Coordinates window contains sliders that correspond to joint coordinates, or degrees of freedom, in the model. To see the Coordinates window, click the **Window** menu and select **Coordinates**. For the current model, the orientation of the pelvis corresponds to the orientation of the model with respect to ground.

*Note: If already opened, you can also view the Coordinates window by clicking its title bar.*

- The first three sliders—pelvis tilt, list, and rotation— correspond to rotations of the pelvis about the Z, X, and Y-axes of the "pelvis" reference frame. To rotate the pelvis about the Z-axis, drag the **pelvis\_tilt slider**. Similarly, to rotate the pelvis about the other two axes, drag the corresponding slider.
- The next three sliders—pelvis tx, ty, and tz— correspond to translations of the pelvis along the X, Y, and Z-axes of the "ground" reference frame. *Note: Rotating and translating the model this way changes the orientation and location of the model with respect to ground, and is different than rotating or translating the model view in the visualizer.*
- The remaining sliders correspond to joint rotations and control a single degree of freedom. To rotate the joints, drag the sliders or type in a desired joint angle in the adjacent textbox.
- Using the tools in the **Poses** menu, you can restore the model's default pose, save the current pose, or set the current pose as the model's new default.
  - For now, restore the default coordinates by clicking the **Poses** button and selecting **Default**.
  - Later on in the tutorial, you will save a new pose. To do this, once you've posed the model, select **New** in the **Poses** menu, type in a name for the pose, and click OK. Your saved pose will appear under "Default" when you click **Poses**.
  - To set a new model default pose, after posing the model as desired, select **Set Default** in the **Poses** menu. You will need to save the model for the new Default Pose to be saved.

Name	Value	Range	Speed
pelvis_tilt	0.000	-90 to 90	0.000
pelvis_list	0.000	-90 to 90	0.000
pelvis_rotation	0.000	-90 to 90	0.000
pelvis_tx	0.000	-5 to 5	0.000
pelvis_ty	0.950	-1 to 2	0.000
pelvis_tz	0.000	-3 to 3	0.000
hip_flexion_r	0.000	-120 to 120	0.000
hip_adduction_r	0.000	-120 to 120	0.000
hip_rotation_r	0.000	-120 to 120	0.000
knee_angle_r	0.000	-120 to 10	0.000
ankle_angle_r	0.000	-90 to 90	0.000

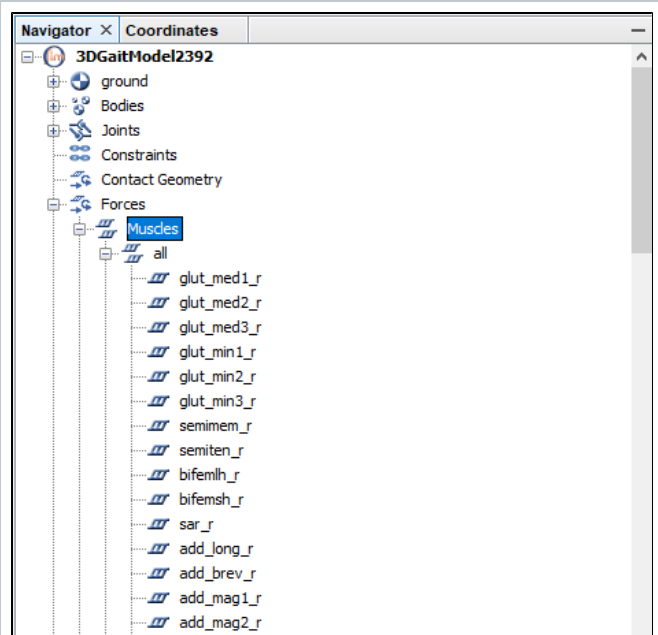
## Muscles in a Model

Muscle-tendon paths are represented in OpenSim by a series of points connected by line segments. To see a list of all the muscles:

- In the Navigator, expand the **3DGaitModel2392** (model name) **Forces**, **Muscles**, and **all** headings.
- To display a single muscle, **right-click** on a specific muscle name under the **all** group, e.g., *glut\_med1\_r*, and select **Display > Show Only** from the popup menu.
- To toggle the display of all muscles, **right-click** on the **Muscles** or **all** heading, and select **Display > Show** or **Display > Hide**
- Rather than a single line of action, some muscles can be represented by multiple lines. In this model, the gluteus medius is an example of a muscle represented by multiple lines of action (e.g., *glut\_med1\_r*, *glut\_med2\_r*, *glut\_med3\_r*).

For some muscles, two points, the muscle origin and insertion, are sufficient to describe the muscle path. For other muscles that wrap over bones or are constrained by retinacula, intermediate *wrapping* or *via* points must be defined. To view these *wrapping* points:

- Restore the default model pose by clicking the **Poses** button and selecting **Default**. Then zoom in on the right knee joint.
- Right click on the **R\_knee\_ext** muscle group and select **Show only**.
- Fully flex the right knee using the **knee\_angle\_r** Coordinates slider.
- Notice that wrapping points are introduced in some of the knee extensors at certain knee angles, such that the muscle paths develop kinks and appear to wrap around the bones.
- Some muscles in the lower limb model pass through the bones or deeper muscles at extreme ranges of motion.



## Questions

### 1. Degrees of Freedom

- Use the Coordinates panel to view the degrees of freedom of the model. How many degrees of freedom, in total, does the model have? List the degrees of freedom of the right leg.
- All models are approximations. Compare the degrees of freedom in the model to the degrees of freedom in your lower limbs. Give an example of a joint motion in the model that has been simplified. Give an example of a motion that is not included in this model.

### 2. Muscles

- How many muscles are in the model? How does this compare to the number of degrees of freedom in the model? What is the minimum number of muscles required to fully actuate the model?  
*Hint: Full actuation of the knee, for example, means both knee flexion and knee extension.*
- Name two muscles, other than the gluteus medius, in the model that are represented by multiple lines of action. Why do you think these muscles are represented in this way?  
*Hint: Other muscles with multiple lines of action use the same naming convention as the gluteus medius.*
- Which knee extensor muscles have wrapping points? At what knee angles do the wrapping points appear for each of those knee extensors? A muscle may have more than one wrapping point.

### 3. Modeling Limitations

- Zoom in on the right hip, and display only the *glut\_max3\_r* muscle (right hip extensors group). Examine this muscle for the full range of hip flexion angles. What problems do you see with the path of *glut\_max3\_r* through the range of motion? In what ways are point-to-point representations of muscle paths a simplification of musculoskeletal geometry?

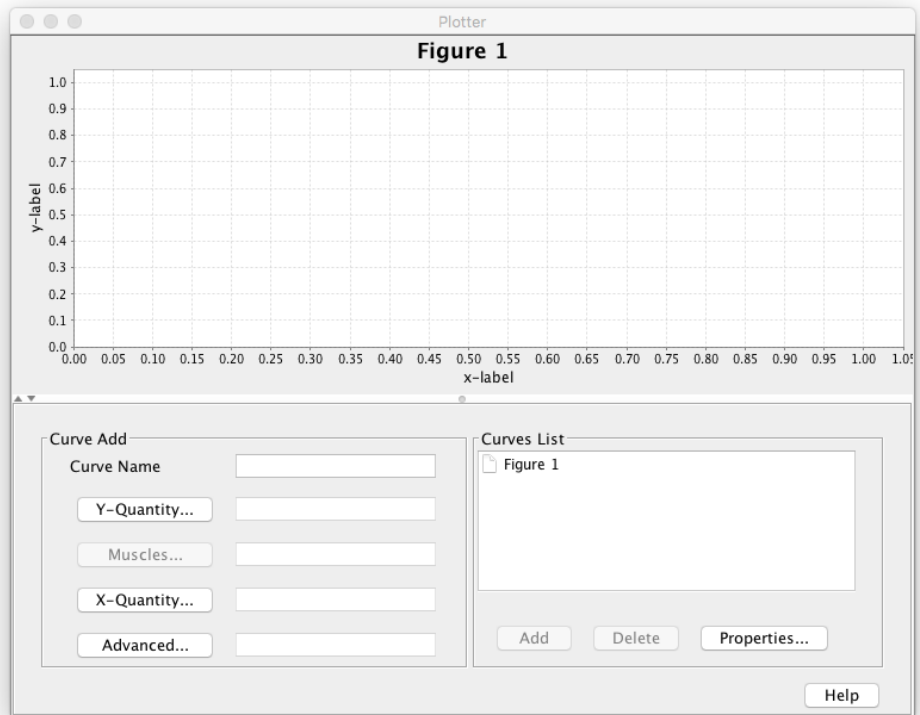
## III. Joint Angles, Muscle-tendon Lengths, & Moment Arms

In this section, you will investigate how muscle-tendon lengths and moment arms depend on limb configuration. Musculoskeletal geometry is very important to the function of muscles and to the development of quantitative musculoskeletal models. Muscle-tendon forces depend on the muscle-tendon length, and joint moments depend on both muscle-tendon forces and moment arms. Therefore, accurate specification of musculoskeletal geometry is essential in developing an accurate model for predicting muscle-tendon forces and joint moments.

## Using the Plotter

OpenSim's Plotter allows you to plot muscle-tendon properties, such as length, moment arm, force, and joint moment. To generate a plot of *fiber-length vs. knee angle* for the *rectus femoris* and *vastus intermedius* muscles:

- Return the model to its original pose by clicking **Poses > Default** in the Coordinates window.  
*Note: Plots are created for the current configuration of the model. Your plots will now be made for the default pose.*
- To open a new plot, click the **Tools** menu and select **Plot**. In the plotter window, click the **Y-Quantity** button and select **fiber-length**. This variable will appear on the y-axis.
- After selecting an appropriate Y-Quantity, you must select the muscles for which you want to generate curves. Click on the **Muscles** button and a menu will appear.
- To find muscles more quickly, you can filter the muscles by muscle group. Choose the **model** option and use the **group** drop down menu to select **R\_knee\_ext**. The muscles list should now only show the muscles in the right knee extensors group.
- Select *rectus femoris* and *vastus intermedius* from the list by **clicking the checkboxes** labeled **rect\_fem\_r** and **vas\_int\_r**.  
*Note: You do not have to close the muscles window as long as the plotter window is open, and your selections are immediately updated in the Muscles textbox. This can be helpful when creating multiple curves on the same plot, which you will do in a few more steps.*



- Click **X-Quantity** and select **knee\_angle\_r**. This variable will appear on the x-axis.
- To add a title to the plot, click the **Properties** button and type **Fiber-Length vs. Knee Angle** into the textbox under the **Title** tab. Explore the plot properties, and then click **OK**.
- To add the curves to the plot, click **Add**.  
*Note: The plots use the following SI units: meters (length), Newtons (force), Newton-meters (moment).*
- Do *not* close the plot window, as you will be adding more curves in the next section.

## Questions

### 4. Muscle Fiber Length vs. Joint Angle

- a. Study the plot of muscle fiber length vs. knee angle. For each of the rectus femoris and vastus intermedius, do you expect the fiber-length curve be different if the right hip was flexed? Why or why not?
- b. In the Coordinates window, adjust the model's **right hip flexion to 45 degrees** (save the pose as **r\_hip\_flex\_45**), add rectus femoris and vastus intermedius fiber-length curves for 45° hip flexion. Compare the muscle curves for the model with an unflexed hip you plotted previously to the curves for the model that you just plotted. How have the curves changed? Explain your findings. How can bi-articular muscles complicate analysis?  
*Note: To select multiple curve names, hold down Ctrl (PC) or Command (Mac) while selecting. To print or save a plot, right-click on the plot and select Print or Export Image.*

### 5. Muscle Moment Arm vs. Joint Angle

Return the model to its original position with no hip flexion (click **Poses > Default**). Now plot the knee extension moment arm vs. knee angle for the right rectus femoris and vastus intermedius muscles.

- In a new plotter window, click **Y-Quantity > moment arm > knee\_angle\_r** and click **X-Quantity > knee\_angle\_r**.
  - Select the right rectus femoris (**rect\_fem\_r**) and vastus intermedius (**vas\_int\_r**) muscles as before.
  - Set the plot title to **Knee Extension Moment Arm vs. Knee Angle**
  - **Add** the curves to the plot.
- a. What are the peak moment arms for each muscle and at what knee angle do they occur?  
*Note: If you hover the cursor over a curve, a tool tip will give the coordinates at that particular point.*
- b. At what knee angle(s) are the moment arm curves not smooth (i.e. have points where the derivative is not continuous)? What do you think causes this? *Hint: Look at Question 2.c*

Feel free to make more plots for other limb positions, muscles, and/or joints. When you are ready to continue with the tutorial, close the plotter window and close the *3DGaitModel2392* model by clicking the **File** menu and selecting **Close Model**. Do not save the model settings to file— we close the model to ensure that any prior modifications made while exploring don't affect the rest of the tutorial.

## IV. Assessment of Hamstrings Length During Crouch Gait

In this final section of the tutorial, you will use OpenSim to investigate a possible cause of crouch gait, one of the most common walking abnormalities among individuals with cerebral palsy. It is characterized by excessive flexion of the knee during stance phase, which is often accompanied by exaggerated flexion and internal rotation of the hip. One hypothesized cause of crouch gait is short hamstrings, and orthopedic surgeons will sometimes lengthen the hamstrings of such patients in an attempt to improve their posture and gait. However, other causes of excessive knee flexion are possible (e.g. weak ankle plantarflexors), and lengthening the hamstrings can compromise these muscles' force-generation capabilities [3]. How can a surgeon determine whether a hamstring lengthening procedure is warranted?



One possible way to judge whether a patient's hamstrings are shorter than "normal" is to develop a musculoskeletal model and compare the length of the hamstrings during the patient's crouch gait cycle to the length of the hamstrings during a normal gait cycle. Suppose that an orthopaedic surgeon has brought you some kinematic data for a patient who walks with a crouch gait. The surgeon is contemplating whether to operate and wants your opinion.

## Loading a Motion




Re-open the **gait2392.osim** model. To animate the model, you need to load an associated motion file into OpenSim.

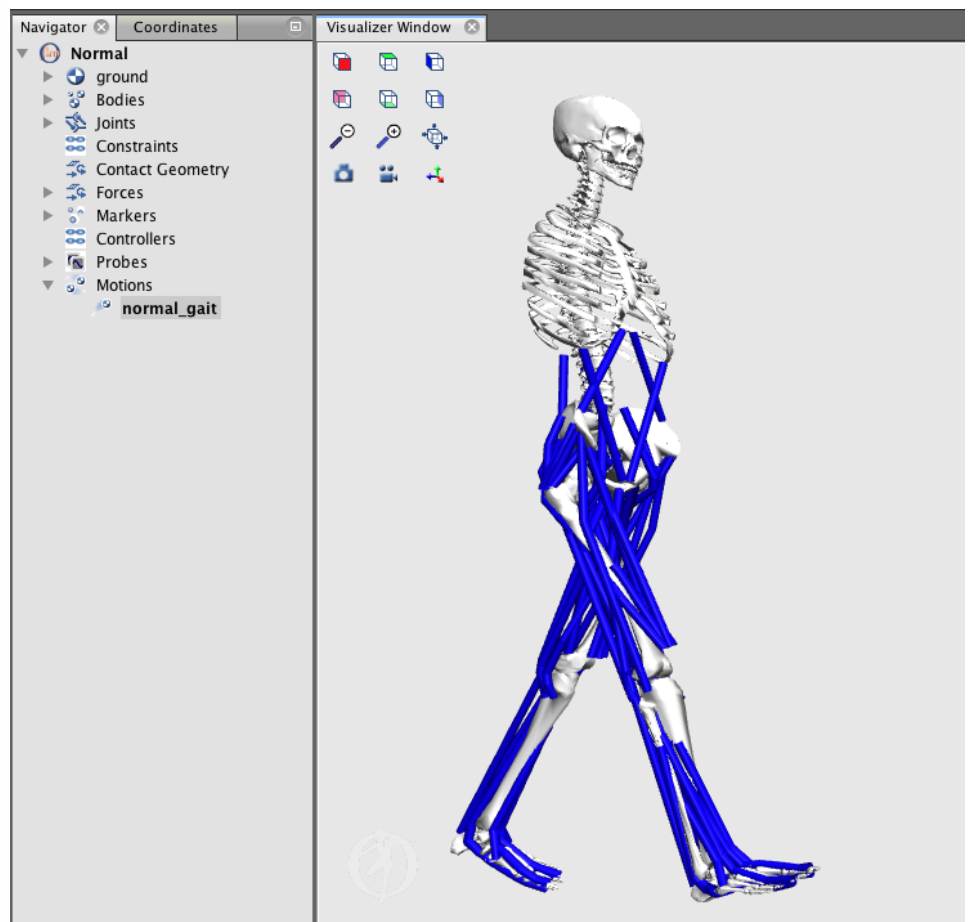
- Click the **File** menu and select **Load Motion**. Ensure you are in the **Gait23921 Tutorial1** directory, select the file **normal.mot**, and click **Open**. This motion file contains kinematics for a normal gait. Re name the opened model to **Normal** by **right-clicking** on the model name in the Navigator and selecting **Rename** from the popup menu.

*Note: Renaming in the Navigator pane only changes the display name, it does not affect the file name of the model.*

After loading a motion, its name will appear in the motion textbox, located on the toolbar. Additionally, a new branch will appear in the Navigator titled **Motions**. Expand it to see all motions loaded for a particular model, as shown. The color of the muscles change to blue after the motion is loaded.

## Motion Slider

The motion slider corresponds to the current motion file. To play the current motion, drag the motion slider. To animate the model, use the **video control** buttons, e.g., click **play** . There are also buttons to **loop** , **pause** , and control the **speed** of the animation.



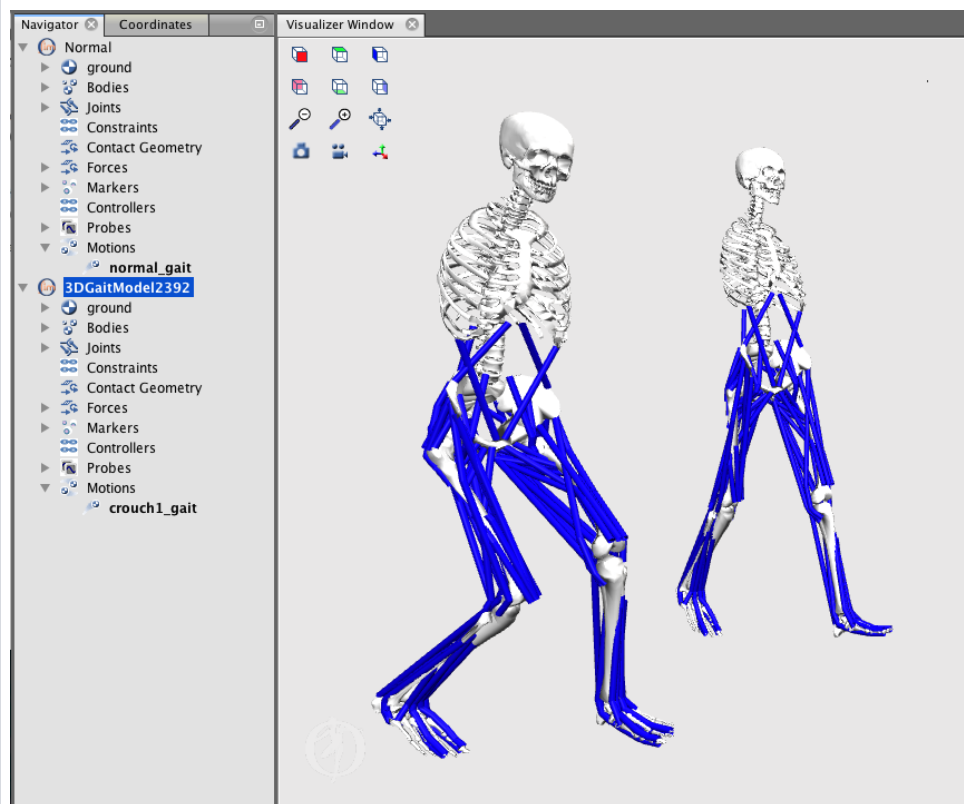
## Multiple Models and Motions

OpenSim has the ability to load multiple models simultaneously. Follow these steps to open a second model and load a new motion:

- With the Normal model open in the Navigator, open a second version of the same model, **gait 2392.osim**, and rename it to Navigator to **Crouch**. The second model you loaded automatically becomes the *current* model. Any action, such as loading a motion, will be applied only to the current model. Load the motion file **crouch h1.mot**, which is in the **Gait2392\Tutorial 11** folder.

*Note: If you do not see both models after loading, zoom out. Throughout the rest of the tutorial, these two models will be referred to as **Normal** and **Crouch**.*

- OpenSim can synchronize multiple motions, allowing you to animate multiple models simultaneously. To do this, expand the **Motions** branch of each model in the Navigator, hold down **Ctrl** (Windows) or **Command** (Mac), and select both motions names such that each name is highlighted. **Right-click** on either motion name, then select **Sync. Motions** from the popup menu, as shown.



## Questions

### 6. Range of Motion

- a. Synchronize and play the normal gait and crouch gait. Be sure to loop the animation, adjust the play speed, and rotate the models. Visually compare the two motions. From your observations, qualitatively describe the general differences in kinematics (joint coordinates) between the normal and crouch gait motions.

Now quantitatively compare knee flexion angles over the crouch and normal gait cycles.

- Open a new **Plot** window.
- Make the *Normal* model current by double-clicking its name, **Normal**, in the Navigator. It should become bold-faced.
- In the plot window, click **Y-Quantity**, select **normal\_gait**, and select **knee\_angle\_r**. Click **OK**.
- Click **X-Quantity** and select **normal\_gait**. Click **OK**.
- Edit the text in the **Curve Name** textbox to read **Normal Gait**.
- To add the curve of *right knee angle vs. gait cycle*, click **Add**.
- Make the *Crouch* model current by selecting it (double-click) in the Navigator. It should become bold-faced.
- In the same plotter window, click **Y-Quantity**, select **crouch1\_gait**, and select **knee\_angle\_r**. Click **OK**.
- Click **X-Quantity** and select **crouch1\_gait**. Click **OK**.
- In the **Curve Name** textbox edit the text to read **Crouch Gait**, then click **Add**.

b. Draw the plot of the knee angle curve for a normal gait cycle. Label the times at which heel strike and toe-off occur, and the stance and swing intervals.

c. What is the range of motion for knee flexion during stance phase for normal gait?

d. How does knee flexion range of motion for crouch gait compare to that of normal gait?

## 7. Hamstrings Length

An orthopedic surgeon believes that a patient may benefit from a hamstring lengthening surgery. You are tasked to compare the hamstrings (semite ndinosus) length over a patients crouch gait cycle to the hamstrings length for a "normal" gait cycle.

Plot the semitendinosus muscle-tendon length over the crouch and gait cycles

- To delete the previous curves, select all the names from the **Curves List** and click **Delete**.
- Make the *normal* model current by selecting it from the **Model** drop down menu.
- Click **Y-Quantity** and select **muscle-tendon length**.
- Click on **Muscles** and select **semiten\_r** from the list. Click **Close**.  
*Note: To quickly find the semiten\_r, type semi into the pattern textbox.*
- Click **X-Quantity** and select **normal\_gait**.
- In the **Curve Name** textbox edit the text to read **Normal Gait**.
- To add the curve of *hamstrings length vs. gait cycle*, click **Add**.
- To make a similar curve for the crouch gait data, make the *crouch* model current. Then, click on **Y-Quantity** and re-select **muscle-tendon length**.
- Click on **Muscles** and select **semiten\_r**.
- Click **X-Quantity** and select **crouch1\_gait**.
- In the **Curve Name** textbox, edit the name to read **Crouch Gait**, and then click **Add**.

a. Study the curves. Based on the plot, how do the peak hamstring lengths in normal and crouch gait compare? For this patient, would you recommend a hamstrings lengthening surgery?

b. What are some limitations of your analysis?

## 8. Additional Crouch Gait Files (optional)

The orthopaedic surgeon cares for three other patients who walk with a crouch gait. Repeat the above analysis for motion files *crouch2.mot*, *crouch3.mot*, and *crouch4.mot*. Note that you can associate more than one motion with a model. *Would your recommendations to the surgeon be any different for these patients?* If you would like to learn more about this type of analysis, please read reference [3].

## Credits

Allison Arnold and Scott Delp with help from many others.

## References

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