Leg Muscle Forces during Gait[[1]](#footnote-1)

# I. Introduction

OpenSim is a freely-available, user-extensible software system for developing musculoskeletal models and for simulating and analyzing movement. By creating dynamic simulations of movement that combine anatomical models with the physics of the musculoskeletal system, researchers can investigate elements of biomechanics that are difficult to study through experimentation alone.

## Objectives

This tutorial will take you through a typical workflow using OpenSim. You will use several of the OpenSim tools to estimate the muscle forces of a human leg model during stance and swing phases of gait. In [Part I: Leg Muscle Force Estimation in Swing](http://simtk-confluence.stanford.edu:8080/display/OpenSim/Part+I%3A+Leg+Muscle+Force+Estimation+in+Swing), you will

* Visualize an Inverse Kinematic (IK) solution,
* Use the Excitation Editor to generate muscle excitations for a forward dynamic simulation,
* Use the Static Optimization Tool to estimate muscle excitations when muscle-tendon dynamics are ignored, and
* Use the Computed Muscle Control (CMC) Tool to estimate muscle excitations in a forward dynamic simulation.

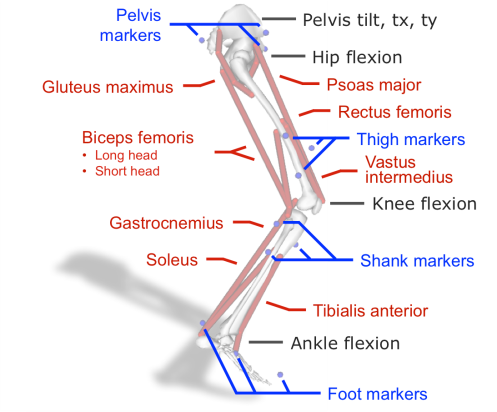
In [Part II: Leg Muscle Force Estimation in Stance](http://simtk-confluence.stanford.edu:8080/display/OpenSim/Part+II%3A+Leg+Muscle+Force+Estimation+in+Stance), you will

* Use the Inverse Dynamics (ID) Tool to estimate joint torques and residual forces,
* Use the Residual Reduction Algorithm (RRA) to find model parameter values that reduce the residual forces predicted by the ID solution, and
* Use CMC to estimate muscle excitations in a forward dynamic simulation.

## Acknowledgements

This example was created by Ajay Seth, Samuel Hamner, Kat Steele, Jennifer Hicks, Matt DeMers, Thomas Uchida, Daniel Jacobs, and Scott Delp. It was developed for teaching a workshop at the International Society of Biomechanics and refined for Prof. Delp's class at Stanford University.

## Model

 This is a simplified single leg model (leg6dof9musc.osim) that is packaged with the OpenSim distribution. The leg model consists of 7 bodies representing four physiological segments (pelvis, thigh, shank, and foot). The configuration of the system is described by 6 generalized coordinates (pelvis\_tilt, pelvis\_tx, pelvis\_ty, hip\_flexion, knee\_angle, and ankle\_angle). The musculoskeletal forces are generated by 9 muscles (psoas major, gluteus maximus, rectus femoris, vastus intermedius, biceps femoris long head, biceps femoris short head, tibialis anterior, medial gastrocnemius, and soleus). This simple model is not intended for research.

## Getting Started

The majority of the files required for this example can be found in the Models directory of your OpenSim installation (e.g., C:\OpenSim 3.0\Models\Leg6Dof9Musc).

# II. Leg Muscle Force Estimation in Swing

## Explore the model and the Forward Dynamics Tool

*Objective: Visualize an inverse kinematic solution of the swing phase using the OpenSim GUI. Run a forward dynamic simulation of the swing phase with no muscle control.*

Open the leg model, load the motion, and view the animation.

Use the File menu in the OpenSim GUI to open the 6-degree-of-freedom, 9-muscle leg model file (leg6dof9musc.osim) and load the swing motion file (leg69\_IK\_swing.mot from the Swing folder). The loaded motion will appear under the Motions tree in the Navigator panel. Animate the swing phase motion using the movie controls located above the view pane.

In the Navigator panel, rename the motion from Results to IK so it is distinct from the motions we will be generating below.

Stop the motion and reset the player to the first time step. In the Coordinates tab, set the current pose of the model (i.e., the initial pose of the inverse kinematics (IK) solution) as the default pose by clicking “Poses >” and selecting “Set Default”. Save the model after changing the default parameters.

Use the Forward Dynamics Tool to create a simulation of the system with no muscle controls.

Open the Forward Dynamics Tool by selecting “Forward Dynamics...” from the Tools menu. Configure the tool as follows:

* In the Input pane, check “Solve for equilibrium for actuator states”, which equilibrates the muscle–fiber and tendon forces at the initial time step.
* In the Time pane, specify the time range corresponding to the IK motion (0.117 to 0.617 seconds).
* In the Output pane, create a new directory in the Swing folder (e.g., <YourWorkingDir>\Swing\FWD\_No\_Controls).
* Save your settings to a file (e.g., leg69\_Setup\_Forward\_No\_Controls.xml).
* Run the simulation. Replay the resulting motion using the movie controls.
* Close the tool.
* In the Navigator, rename the motion to FWD\_unlocked.

Lock the pelvis coordinates and plot simulation results.

In this forward simulation, the model simply falls since there are no ground reaction forces to oppose gravity. In the Coordinates tab, lock the pelvis coordinates (pelvis\_tilt, pelvis\_tx, and pelvis\_ty) to prevent the model from falling. Re-run the Forward Dynamics Tool, making sure to use "FWD\_locked" in the names of the output folder, the settings file, and the resulting motion.

Open the plotter by selecting "Plot..." from the Tools menu. The X and Y quantities for the plot are selected in the Curve Add panel. Any motions displayed under the Motions tree in the Navigator panel can be plotted. External data can also be loaded by clicking "Y-Quantity..." and selecting the "Load file..." option.

Note that the generalized coordinates appear first in the list and the generalized speeds are suffixed with "\_u".

## Simulate swing phase with manually selected excitations

*Objective: Using the Excitation Editor in the OpenSim GUI, find a set of muscle excitations that will match the given swing phase motion.*

Make sure that the pelvis coordinates (pelvis\_tilt, pelvis\_tx, and pelvis\_ty) are locked before proceeding with the remaining sections.

In the previous forward dynamic simulation, no controls were specified for the muscle actuators. As a result, no active muscle forces were generated.

Use the Excitation Editor to generate a set of muscle excitations that track the IK solution.

Read the page on [how to use the excitation editor](http://simtk-confluence.stanford.edu:8080/display/OpenSim/Excitation+Editor) to learn how to select and change points on a muscle excitation curve.

Two downloadable (link top of page) helper files for setting up the excitation editing are : leg69\_Forward\_Default\_Controls.xml and leg69\_Forward\_Default\_States.sto. The first file, leg69\_Forward\_Default\_Controls.xml, adds control information for the muscles in the model. The controller is defined by a set of control nodes (time and value pairs) that are linearly interpolated to form the muscle excitation signal. These nodes can be edited using the Excitation Editor. The second file, leg69\_Forward\_Default\_States.sto, contains the initial coordinates, muscle fiber lengths, muscle activations, and derivatives that completely specify the starting state used in forward simulations. Download the attachments by selecting "Attachments" from the Tools menu in the top-right corner of this page. Save these files in your working folder.

Open the Forward Tool and configure the editor as follows:

* In the Input pane, for Controls, select the XML file that contains the controls of the forward simulation (e.g., leg69\_Forward\_Default\_Controls.xml).
* In the Input pane, for Initial state, select the storage file that contains the initial states of the forward simulation (e.g., leg69\_Forward\_Default\_States.sto).
* Open the Excitation Editor by clicking on the pencil next to the Controls textbox. From the list of muscles, select a muscle capable of generating hip flexion and click OK.
* Increase the excitation of the muscle as desired.
* Save the excitations to a controls file (e.g., leg69\_Forward\_Controls\_<muscle\_name>.xml).
* In the Input pane, for Controls, select the newly created XML file.
* Check the “Solve for equilibrium for actuator states” box.
* Check that the time range matches the original time range for IK.
* Specify a new output directory (e.g., Swing\FWD\_<muscle\_name>).
* Save your settings to a file (e.g., leg69\_Setup\_Forward\_<muscle\_name>.xml).
* Run the simulation and compare the values of the hip flexion, knee angle, and ankle angle coordinates to the inverse kinematics solution.
* Close the tool.

Excite three muscles to minimize the error of the hip flexion, knee angle, and ankle angle coordinates.

* By exciting a single muscle in early swing, reduce the error of the hip flexion coordinate in the forward simulation.
* By exciting a second muscle along with your previous excitation, reduce the error of the hip flexion and knee angle coordinates.
* By exciting a third muscle, reduce the error of the hip flexion, knee angle, and ankle angle coordinates.

## Simulate swing phase with activations from Static Optimization (SO)

*Objective: Using the Static Optimization Tool, find a set of muscle controls for the swing phase. Use the resulting controls in a forward dynamic simulation and compare the results.*

Use the Static Optimization Tool to find a set of muscle controls that approximately matches the IK motion.

Open the Static Optimization Tool and configure it as follows:

* In the Input pane, load the leg69\_IK\_Swing.mot file as the Motion.
* In the Input pane, check the box to filter coordinates and enter a cutoff frequency of 6 Hz.
* In the Objective Function pane, set the muscle activation exponent to 2.0 and check “Use muscle force-length-velocity relation”.
* Set the time range to between 0.117 and 0.617 seconds (if it is not already set).
* Specify the output directory (e.g., Swing\SO).
* Save your settings to a file (e.g., leg69\_Setup\_SO.xml).
* Make sure the pelvis coordinates (pelvis\_tilt, pelvis\_tx, and pelvis\_ty) are locked.
* Run the tool; close the tool when you are finished.

Use the Forward Dynamic Tool to examine the motion using the estimated muscle controls from Static Optimization.

Run a forward dynamic simulation of the swing phase using the controls generated by Static. Configure the Forward Dynamic Tool as follows:

* In the Input pane, navigate to the output folder of the Static Optimization and select the controls file.
* In the Input pane, select the storage file that contains the initial states of the forward simulation (e.g., leg69\_Forward\_Default\_States.sto).
* Check the “Solve for equilibrium for actuator states” box.
* Specify the same time range as before.
* Specify the output directory (e.g., Swing\FWD\_SO).
* Save your settings to a file (e.g., leg69\_Setup\_Forward\_SO.xml).
* Run the tool; close the tool when you are finished.

## Simulate swing phase with excitations from Computed Muscle Control (CMC)

*Objective: Using the CMC Tool, find a set of muscle controls for the swing phase. Use the resulting controls in a forward dynamic simulation and compare the results.*

Use the Computed Muscle Control (CMC) Tool to find a set of muscle controls that approximately matches the IK motion.

Open the CMC Tool and configure it as follows:

* In the Input panel, specify leg69\_IK\_swing.mot as the desired kinematics.
* In the Input panel, specify leg69\_CMC\_Swing\_Tracking\_Tasks.xml as the tracking task.
* Check the box to filter the coordinates and set the cutoff frequency to 6 Hz.
* Include actuator control constraints that define the muscle control limits (e.g., leg69\_muscles\_control\_limits.xml).
* Set the time range to between 0.117 and 0.617 seconds (if it is not already set).
* Choose a “CMC look-ahead window” that is the approximate time in which muscles can change their output forces in response to a change in input controls (use 0.01s).
* Specify the output directory (e.g., Swing\CMC).
* Make sure the pelvis coordinates (pelvis\_tilt, pelvis\_tx, and pelvis\_ty) are locked.
* Run the tool; close the tool when you are finished.

Use the Forward Dynamic Tool to examine the motion using the estimated muscle controls from CMC.

Run a forward dynamic simulation of the swing phase using the controls generated by CMC. Configure the tool as follows:

* In the Input pane, for Controls, select the controls file from the output folder of the previous CMC run.
* In the Input pane, for Initial States, select the states file from the output folder of the previous CMC run.
* Check the “Solve for equilibrium for actuator states” box.
* Check that the time range automatically updated to between 0.147 and 0.617 seconds.
* Specify the output directory (e.g., Swing\FWD\_CMC).
* Run the tool; close the tool when you are finished.

## Questions

Explore the model and the Forward Dynamics Tool

1. *From the IK results, plot hip flexion, knee angle, and ankle angle as functions of time.*
2. *From the FWD\_locked results, plot hip flexion, knee angle, and ankle angle as functions of time.*
3. *Discuss the difference in joint trajectories between the inverse kinematic and forward dynamic simulations.*
4. *Examine the pelvis\_tilt, pelvis\_tx, and pelvis\_ty coordinates of the IK solution, and discuss the effect of locking the coordinates in the forward simulation.*

Simulate swing phase with manually selected excitations

1. *To match the hip flexion, knee angle, and ankle angle coordinates of the inverse kinematic solution, which three muscles did you excite during the forward dynamic simulation?*
2. *Continue adjusting your muscle excitations until you are satisfied with the tracking. Plot the excitations of your three muscles as functions of time.*
3. *Plot the hip flexion, knee angle, and ankle angle coordinates for the IK solution and your forward solution together.*
4. *Discuss your observations regarding the challenge of tracking trajectories with a forward dynamic simulation.*

Simulate swing phase with activations from Static Optimization (SO)

1. *Plot the muscle activation patterns from Static Optimization, then plot the activations from the Forward Simulation with your best set of controls. How do the activations compare? (Tip: When selecting quantities to plot, use the "Filter By Pattern" to help your search. For example, typing "act" will list only the activation signals.)*
2. *Plot the hip flexion, knee angle, and ankle angle coordinates from the SO solution along with the coordinates for the IK solution.*
3. *Run a forward simulation using the controls from the SO solution and plot the hip flexion, knee angle, and ankle angle coordinates along with the coordinates for the IK solution. Why does the forward simulation using the Static Optimization activation signals diverge from the IK solution?*

Simulate swing phase with excitations from Computed Muscle Control (CMC)

1. *Plot the hip flexion, knee angle, and ankle angle coordinates from the CMC solution along with the coordinates for the IK solution.*
2. *Run a forward simulation using the controls from the CMC solution and plot the hip flexion, knee angle, and ankle angle coordinates along with the coordinates for the IK solution. Are the simulated trajectories better or worse than the Static Optimization results? What is responsible for the difference?*

# III. Leg Muscle Force Estimation in Stance

## Find a set of generalized forces that produce the stance motion using Inverse Dynamics

Before you begin working on stance, make sure to unlock the three pelvis coordinates (pelvis\_tilt, pelvis\_tx, pelvis\_ty) that were locked for the swing analysis.

*Objective: Use the Inverse Dynamics Tool in the OpenSim GUI to find a set of applied forces that make the model dynamics consistent with the applied ground reaction forces.*

Associate the ground reaction force (GRF) data with the inverse kinematics trial and visualize the results.

Visualize and associate the stance motion with the model file as follows:

* Use the File menu to load the motion file leg69\_IK\_stance.mot.
* In the Navigator pane, find the motion called "ik trial".
* Right-click "ik trial" and select "Associate Motion Data...".
* Associate the file Stance\leg69\_stance\_grf.mot with the loaded motion.
* Play the animation to ensure the ground reaction forces have been loaded correctly.

Use the Inverse Dynamics Tool to find a set of generalized forces.

Open the Inverse Dynamics (ID) Tool and configure it as follows:

* In the Input pane, select "Loaded motion" and use the "ik trial" motion from the previous step.
* Check the box to filter the coordinates and set the cutoff frequency to 6 Hz.
* Set the time range to between 0.5 and 1.5 seconds.
* Specify an output directory (e.g., <YourWorkingDir>\Stance\ID).
* Select the External Loads tab and check the External Loads box.
* Edit the External Loads settings by clicking the pencil icon to the right of the textbox.
  + Select leg69\_stance\_grf.mot as the "Force data file". This file describes the force applied at the foot's center of pressure (CoP).
  + Select leg69\_IK\_stance.mot as the "Kinematics for external loads".
  + Select "Filter kinematics" and specify a cutoff frequency of 6 Hz.
  + Add the forces listed in the motion file by clicking the "Add..." button.
    - Provide a name (e.g., "Right\_GRF").
    - Apply the force to the calcn\_r body.
    - Check "Applies Force" and select "Point Force".
    - Force Columns: select "ground\_force\_vx" from the first drop-down box; "ground\_force\_vy" and "ground\_force\_vz" will be selected automatically.
    - Point Columns: select "ground\_force\_px" from the first drop-down box; the corresponding "y" and "z" entries will again be populated automatically.
    - The GRF free moment is a torque, so check "Applies Torque".
    - Torque Columns: select "ground\_torque\_x", "ground\_torque\_y", and "ground\_torque\_z".
    - The GRF and CoP are both expressed in the ground (laboratory) frame, so click OK.
    - Click "Save..." and enter a filename for the External Force input (e.g., leg69\_right\_GRF.xml).
    - Click "Save..." and enter a filename for the ID settings (e.g., leg69\_Setup\_ID\_stance.xml).
* Run the tool, then close the Inverse Dynamics Tool window.

## Model refinement through residual reduction

*Objective: Use the Residual Reduction Algorithm (RRA) Tool to find a new set of model parameters that reduces the residual forces.*

Use the RRA Tool to calculate the size of the residuals.

Open the RRA Tool and configure it as follows:

* In the input pane, set the desired kinematics as the IK motion file (e.g., leg69\_IK\_stance.mot).
* Check the box to filter kinematics at 6 Hz.
* In the input pane, specify the tracking tasks for RRA. Specify the task file provided in Stance\leg69\_Tracking\_Tasks.xml. This file specifies the coordinates to be tracked and the corresponding weights. Use the GUI File Editor or an XML editor (e.g., Notepad++) to view the tasks.
* Check "Adjust model". Click on the folder icon, make sure you are in the Stance folder, specify a new model name (e.g., leg6dof9musc\_RRA\_adjusted.osim), and click Save.
* Make the pelvis the "Body COM to adjust". The center of mass of this body will be adjusted to reduce residuals. Typically, the segment that includes the torso is chosen.
* Specify the time range using your analysis from part A (see [Questions: Leg Muscle Force Estimation](http://simtk-confluence.stanford.edu:8080/display/OpenSim/Questions%3A+Leg+Muscle+Force+Estimation), Part II, Question A.5).
* Specify an output directory (e.g., <YourWorkingDirectory>\Stance\RRA).
* Go to the Actuators and External Loads tab and choose "Replace model's force set" to replace the model's muscles with residual and joint motor actuators, since we are creating a torque-driven simulation.
* Click the "Edit..." button next to the "Additional force set files" textbox, then click "Add". Click the folder button next to the red textbox and select leg69\_RRA\_residuals\_motors.xml. Click OK.
* Check the External Loads box and specify the file you created for Inverse Dynamics (e.g., leg69\_right\_GRF.xml).
* Save your settings to an RRA setup file (e.g., leg69\_Setup\_RRA\_stance.xml) and click Run.

After each run of the RRA tool, a new model file will be loaded into the navigator (and also printed) where the COM of the pelvis has been automatically adjusted.  In the messages window, the RRA tool also provides a set of estimated changes to the mass and the COM for all of the segments which would further reduce the residuals needed to match the experimental kinematic and force data.

## Finalize the model through iteration of RRA

*Objective: Create a new model using the output of the RRA Tool. Iteratively run RRA on each new model, adjusting only the pelvis mass and CoM location.*

Use the Navigator to edit the mass properties of the pelvis as recommended by the RRA Tool.

When RRA is complete, a new model with an adjusted pelvis CoM will be loaded into the navigator.  However, the mass of the pelvis is not adjusted by the tool and you will need to manually adjust the mass of the body.

* In the Navigator pane, expand the Bodies tree and select pelvis.
* In the Properties Editor, adjust the mass as recommended by the RRA Tool.
* Rename the model in the Navigator pane (e.g., leg6dof9musc\_adj) by right-clicking on the current model name and selecting "Rename...".
* Click "Save As..." and save the model with a new name (e.g., leg6dof9musc\_RRA\_adjustment.osim).

Perform several iterations of running RRA and adjusting the model until the residual forces and tracking errors have stabilized.

* Re-run RRA with the adjusted model making sure to close and re-open the RRA Tool to ensure the most recent adjusted model is always used.
* Adjust the Pelvis CoM and Mass in accordance with the RRA Tool output messages.
* Increase the tracking task weights for coordinates that show poor tracking.
* Decrease the tracking weight for coordinates that are within 1 degree, since the optimizer can use these coordinates to reduce residuals.
* Iterate until the requested change in pelvis mass is less than 1 kg and the residual forces and coordinate errors follow the suggested thresholds in the table at the bottom of the [Getting Started with RRA](http://simtk-confluence.stanford.edu:8080/display/OpenSim/Getting+Started+with+RRA) page.

## Forward simulation of stance with CMC

*Objective: Use the CMC Tool to determine a set of muscle excitations, activations, and forces that generate a forward dynamic simulation of the stance phase of gait.*

Configure the actuators used in the CMC Tool.

Create a new actuator file that penalizes the use of residual motors:

* Ensure you have loaded your final model from the previous section on RRA.
* From the Edit menu, select "File (.xml)..." and open the leg69\_RRA\_residuals\_motors.xml file, which contains information on the residual and motor actuators necessary for CMC.
* Reduce the optimal force of the joint motors to 1 so that they are penalized during CMC and muscles are favored to generate joint moments.
* Save the edited actuators as a new file (e.g., leg69\_CMC\_residuals\_motors.xml).

Use the CMC Tool to calculate the muscle excitations, activations, and forces of the stance phase.

Open the CMC Tool and configure it as follows:

* In the Input panel, specify the desired kinematics as the output from RRA (e.g., leg6dof9musc\_Kinematics\_q.sto).
* Note that no filtering is required: the kinematics are smooth since they resulted from a simulation.
* Ensure you are using the adjusted RRA model and the corresponding kinematics.
* Apply tracking tasks. Use the same tasks file as you used for RRA.
* Include actuator control constraints that define the control limits for each muscle (e.g., leg69\_muscles\_residuals\_motor\_control\_limits.xml).
* Specify the same time range as before.
* Specify the output directory (e.g., <YourWorkingDirectory>\Stance\CMC).
* Under the Actuators and External Loads tab, select "Append to model's force set" to include joint motor and residual actuators in addition to existing muscles in the model. Use the "Edit..." button to specify that leg69\_CMC\_residuals\_motors.xml is to be appended.
* Specify the external loads (same as for RRA).
* Save your CMC settings to a file.
* Run the tool.

Tips and tricks for CMC

* One common way for CMC to fail is when the tool is unable to find a set of muscle forces that can accurately reproduce the joint dynamics.  Consider reducing the tracking weights until you run successfully completes.  Make sure to rerun RRA and use the adjusted model output from the RRA tool in CMC when you adjust the tasks.
* Check the troubleshooting tips on the [Getting Started with CMC](http://simtk-confluence.stanford.edu:8080/display/OpenSim/Getting+Started+with+CMC) page.

## Questions

Find a set of generalized forces that produce the stance motion using Inverse Dynamics

1. *Plot the applied forces and torques that act on the pelvis (i.e., pelvis\_tilt\_moment, pelvis\_tx\_force, and pelvis\_ty\_force) as functions of time. The data is in the ID/inverse\_dynamics.sto file.*
2. *What does the pelvis\_ty\_force curve tell you about the force applied during stance?*
3. *Plot the experimentally-measured vertical ground reaction forces (ground\_force\_vy and 1\_ground\_force\_vy) from the leg69\_stance\_grf.mot file and the pelvis\_ty\_force as functions of time.*
4. *How do the ground forces compare to the pelvis\_ty\_force?*
5. *Given that model consists of only a single leg and pelvis, in what time range is it reasonable to use this model with the given kinematics and measured forces?*

Model refinement through residual reduction

1. *Why does the pelvis translate substantially in the y-direction (pelvis\_ty coordinate) during the simulation?*
2. *Plot the RRA residual actuator forces (i.e., MZ, FX, and FY) from leg6dof9musc\_controls.sto.*
3. *Open the Messages pane and locate the recommended overall mass adjustment from the last run of RRA (e.g., "pelvis: orig mass = 10.7538, new mass = xxxxx"). Note that the units are in kilograms (kg). What is the recommended mass adjustment? Why would the mass adjustment be so large?*

Finalize the model through iteration of RRA

1. *For your final RRA iteration, plot the tracking error values from the RRA/leg6dof9musc\_pErr.sto file.*
2. *For your final RRA iteration, list the weights of all coordinates in tracking tasks.*
3. *For your final RRA iteration, which coordinate has the maximum tracking error and was is the maximum tracking error value?*

Forward simulation of stance with CMC

1. *Plot the muscle activation patterns from the states file leg6dof9musc\_added\_mass\_states.sto. (Tip: When selecting quantities to plot, use the "Filter By Pattern" to help your search. For example, typing "act" will list only the activation signals.)*
2. *Are the simulated activations for the vastus intermedius (vas\_int\_r.activation) and gastrocnemius medialis (med\_gas\_r.activation) close to what you would expect?*
3. *Plot the CMC residual joint moments (hip\_flexion\_r\_moment, knee\_angle\_r\_moment, and ankle\_angle\_r\_moment) as functions of time.*
4. *Are the moments substantial? Does the plot give you confidence in the predicted muscle forces?*
5. *Plot the CMC residual actuator forces (i.e., MZ, FX, and FY) as functions of time.*
6. *How large are the residual joint moments and residual actuator forces predicted by CMC as a percentage of the body weight of the model? Note: Residuals less than 2% of body weight are considered acceptable.*

# References

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# 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. From the IK results, plot hip flexion (1pt), knee angle (1pt), and ankle angle (1pt) as functions of time. | 3 |
| 1. From the FWD\_locked results, plot hip flexion (1pt), knee angle (1pt), and ankle angle (1pt) as functions of time. | 3 |
| 1. Discuss the difference in joint trajectories between the inverse kinematic and forward dynamic simulations (1pt). | 1 |
| 1. Examine the pelvis\_tilt, pelvis\_tx, and pelvis\_ty coordinates of the IK solution, and discuss the effect of locking the coordinates in the forward simulation (3pts). | 3 |
| 1. To match the hip flexion, knee angle, and ankle angle coordinates of the inverse kinematic solution, which three muscles did you excite during the forward dynamic simulation? (3pts) | 3 |
| 1. Continue adjusting your muscle excitations until you are satisfied with the tracking. Plot the excitations of your three muscles as functions of time (3pts). | 3 |
| 1. Plot the hip flexion, knee angle, and ankle angle coordinates for the IK solution and your forward solution together (3pts). | 3 |
| 1. Discuss your observations regarding the challenge of tracking trajectories with a forward dynamic simulation (1pt). | 1 |
| 1. Plot the muscle activation patterns from Static Optimization, then plot the activations from the Forward Simulation with your best set of controls. How do the activations compare? (1pt) | 1 |
| 1. Plot the hip flexion, knee angle, and ankle angle coordinates from the SO solution along with the coordinates for the IK solution (3pts). | 3 |
| 1. Run a forward simulation using the controls from the SO solution and plot the hip flexion, knee angle, and ankle angle coordinates along with the coordinates for the IK solution (3pts). Why does the forward simulation using the Static Optimization activation signals diverge from the IK solution (1pt)? | 4 |
| 1. Plot the hip flexion, knee angle, and ankle angle coordinates from the CMC solution along with the coordinates for the IK solution (3pts). | 3 |
| 1. Run a forward simulation using the controls from the CMC solution and plot the hip flexion, knee angle, and ankle angle coordinates along with the coordinates for the IK solution (3pts). Are the simulated trajectories better or worse than the Static Optimization results (1pt)? What is responsible for the difference (1pt)? | 5 |
| 1. Plot the applied forces and torques that act on the pelvis (i.e., pelvis\_tilt\_moment (1pt), pelvis\_tx\_force (1pt), and pelvis\_ty\_force (1pt)) as functions of time. The data is in the ID/inverse\_dynamics.sto file. | 3 |
| 1. What does the pelvis\_ty\_force curve tell you about the force applied during stance (1pt)? | 1 |
| 1. Plot the experimentally-measured vertical ground reaction forces (ground\_force\_vy (1pt) and 1\_ground\_force\_vy (1pt)) from the leg69\_stance\_grf.mot file and the pelvis\_ty\_force (1pt) as functions of time. | 3 |
| 1. How do the ground forces compare to the pelvis\_ty\_force (1pt)? | 1 |
| 1. Given that model consists of only a single leg and pelvis, in what time range is it reasonable to use this model with the given kinematics and measured forces (1pt)? | 1 |
| 1. Why does the pelvis translate substantially in the y-direction (pelvis\_ty coordinate) during the simulation (1pt)? | 1 |
| 1. Plot the RRA residual actuator forces (i.e., MZ (1pt), FX (1pt), and FY (1pt)) from leg6dof9musc\_controls.sto. | 3 |
| 1. Open the Messages pane and locate the recommended overall mass adjustment from the last run of RRA (e.g., "pelvis: orig mass = 10.7538, new mass = xxxxx"). Note that the units are in kilograms (kg). What is the recommended mass adjustment (1pt)? Why would the mass adjustment be so large (1pt)? | 2 |
| 1. For your final RRA iteration, plot the tracking error values from the RRA/leg6dof9musc\_pErr.sto file (1pt). | 1 |
| 1. For your final RRA iteration, list the weights of all coordinates in tracking tasks (1pt). | 1 |
| 1. For your final RRA iteration, which coordinate has the maximum tracking error (1pt) and was is the maximum tracking error value (1pt)? | 2 |
| 1. Plot the muscle activation patterns from the states file leg6dof9musc\_added\_mass\_states.sto (1pt). | 1 |
| 1. Are the simulated activations for the vastus intermedius (vas\_int\_r.activation) (1pt) and gastrocnemius medialis (med\_gas\_r.activation) (1pt) close to what you would expect? | 2 |
| 1. Plot the CMC residual joint moments (hip\_flexion\_r\_moment (1pt), knee\_angle\_r\_moment (1pt), and ankle\_angle\_r\_moment (1pt)) as functions of time. | 3 |
| 1. Are the moments substantial (1pt)? Does the plot give you confidence in the predicted muscle forces (1pt)? | 2 |
| 1. Plot the CMC residual actuator forces (i.e., MZ (1pt), FX (1pt), and FY (1pt)) as functions of time. | 3 |
| 1. How large are the residual joint moments and residual actuator forces predicted by CMC as a percentage of the body weight of the model (1pt)? | 1 |
| **Total** | **67** |

1. This lab adapted from <http://simtk-confluence.stanford.edu:8080/display/OpenSim/The+Strength+of+Simulation%3A+Estimating+Leg+Muscle+Forces+in+Stance+and+Swing> [↑](#footnote-ref-1)