# Tutorial 3 - Scaling, Inverse Kinematics, and Inverse Dynamics



> 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.

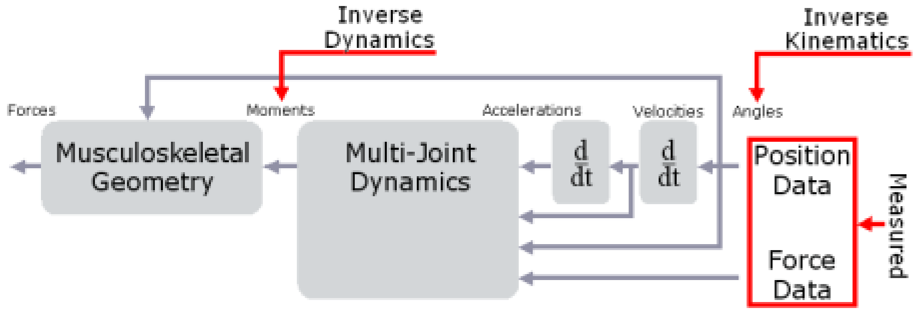
## I. Objectives

### Purpose

The purpose of this tutorial is to demonstrate how OpenSim solves an inverse kinematics and dynamics problem using experimental data. To diagnose movement disorders and study human movement, biomechanists frequently ask human subjects to perform movements in a motion capture laboratory and use computational tools to analyze these movements. A common step in analyzing a movement is to compute the joint angles and joint moments of the subject during movement. OpenSim has tools for computing these quantities:

1. *Inverse kinematics* is used to compute joint angles.
2. *Inverse dynamics* is used to compute net joint reaction forces and net joint moments.

*Inverse kinematics* computes the joint angles for a musculoskeletal model that best reproduce the motion of a subject. *Inverse dynamics* then use joint angles, angular velocities, and angular accelerations of the model, together with the experimental ground reaction forces and moments, to solve for the net reaction forces and net moments at each of the joints. The schematic below shows an overview of the inverse kinematics and inverse dynamics problems.




In this tutorial, you will:

- Become familiar with OpenSim's Scale, Inverse Kinematics and Inverse Dynamics tools
- Solve an inverse kinematics and inverse dynamics problem using experimental data
- Interpret the results of the inverse dynamics solution
- Investigate the dynamic inconsistencies that arise during inverse dynamics

### Format

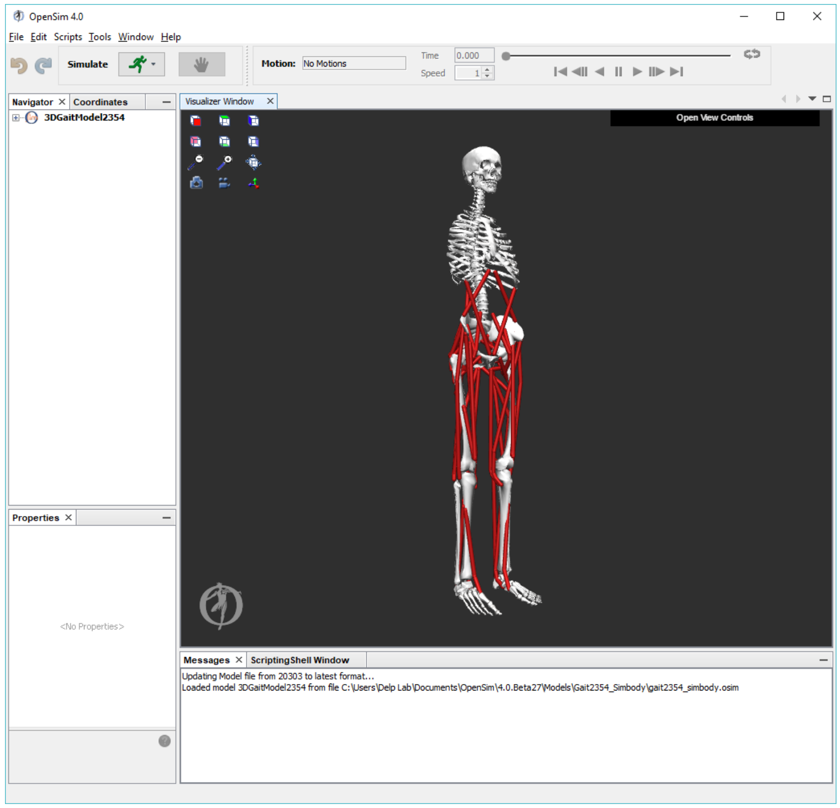
Each section of the tutorial guides you in using certain tools within and asks you to answer a few questions. The menu titles and option names you must select and any commands you must type to run OpenSim will appear in **boldface**. The questions can be answered based on information from OpenSim and basic knowledge of the human musculoskeletal system. After you complete the tutorial, feel free to explore OpenSim and the other analysis tools further on your own. Depending on the amount of exploration you do, this tutorial should take 1-2 hours to complete.

## II. Generic Musculoskeletal Model

In this tutorial, you will be using a generic musculoskeletal model with 23 degrees of freedom and actuated by 54 muscles entitled 3DGaitModel2354. Note: Detailed information about the model can found on the Gait2392 and 2354 Models page

To load the generic musculoskeletal model into OpenSim:

- Click the **File** menu and select **Open Model**.
- Find the ***Gait2354_Simbody*** folder in your default OpenSim resources directory— \Documents\Open Sim\Models for PC and Mac.
  Note: When you first launch OpenSim, you are prompted to provide a path to install the resources folder, the default is in your systems Documents folders.
- Open the ***Gait2354_Simbody*** folder, select the file ***gait2354_simbody.osim***, and click **Open**.

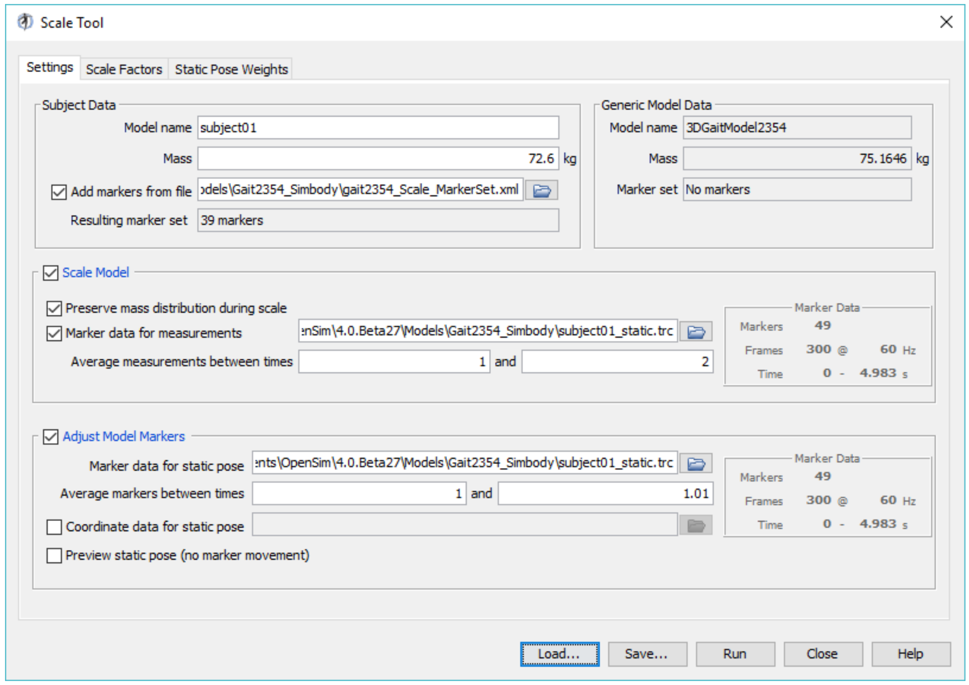



## III. Scaling A Musculoskeletal Model

Subject-specific modeling involves (i) **scaling** a generic musculoskeletal model to modify the anthropometry, or physical dimensions, of the generic model so that it matches the anthropometry of a particular subject and (ii) **registering** the markers placed on the model to match the locations on the subject. **Scaling** and **Registration** are the most important steps in solving inverse kinematics and inverse dynamics problems because IK and ID solutions are sensitive to the accuracy of the scaling and registration.

To scale the generic model and register the markers:

- Click the **Tools** menu and select **Scale Model**.
- At the bottom of the *Scale Tool* dialog, click **Load** to input a settings file.
- In the file browser, ensure that you are in the ***Gait2354*** folder, select the file ***subject01_Setup_Scale.xml*** and click **Open**.



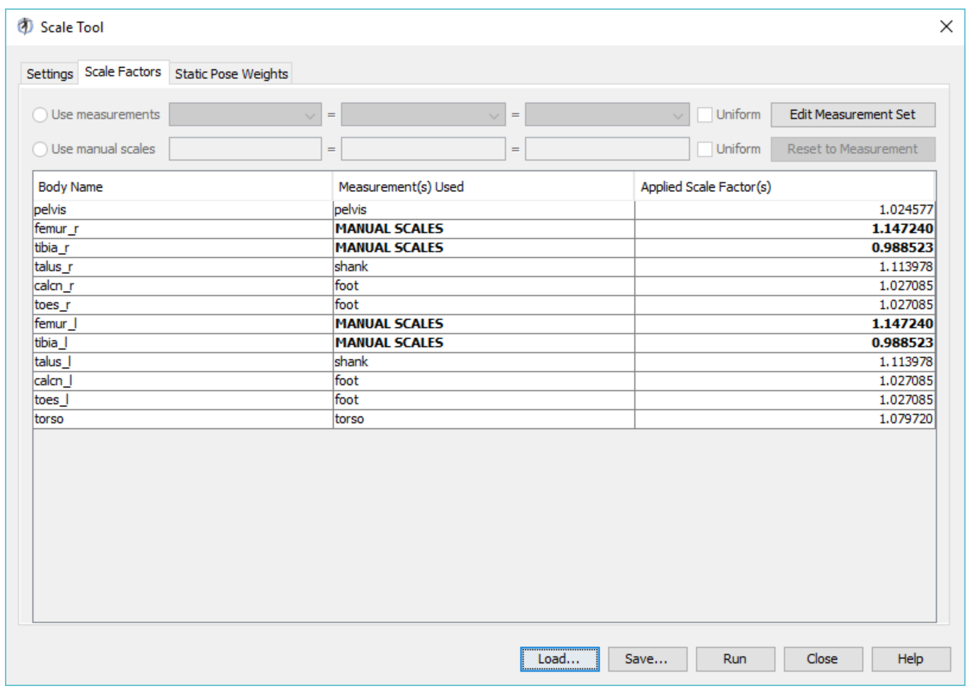

This Scale Setup file is an *xml* file that contains pre-configured settings to scale and register the generic gait2354 musculoskeletal model to the dimensions of a subject that we have experimental data for. A detailed explanation of the Scale Tool can be found on the Scaling page of the documentation.

## Model Scaling

In OpenSim, the scaling step adjusts both the dimensions of the body segments, as well as the mass properties (mass and inertia tensor). Scaling can be performed using a combination of two methods:

*(1) Manual Scaling: Scaling that allows the user to scale a segment based on some predetermined scale factor. Manual scaling is sometimes necessary when suitable data are not available, or if the scale factors were determined using an alternative algorithm.*

*(2) Measurement-based Scaling*: Scaling that determines scale factors for a body segment by comparing distance measurements between specified landmarks on the model, known as *model markers*, and the corresponding *experimental marker* positions.

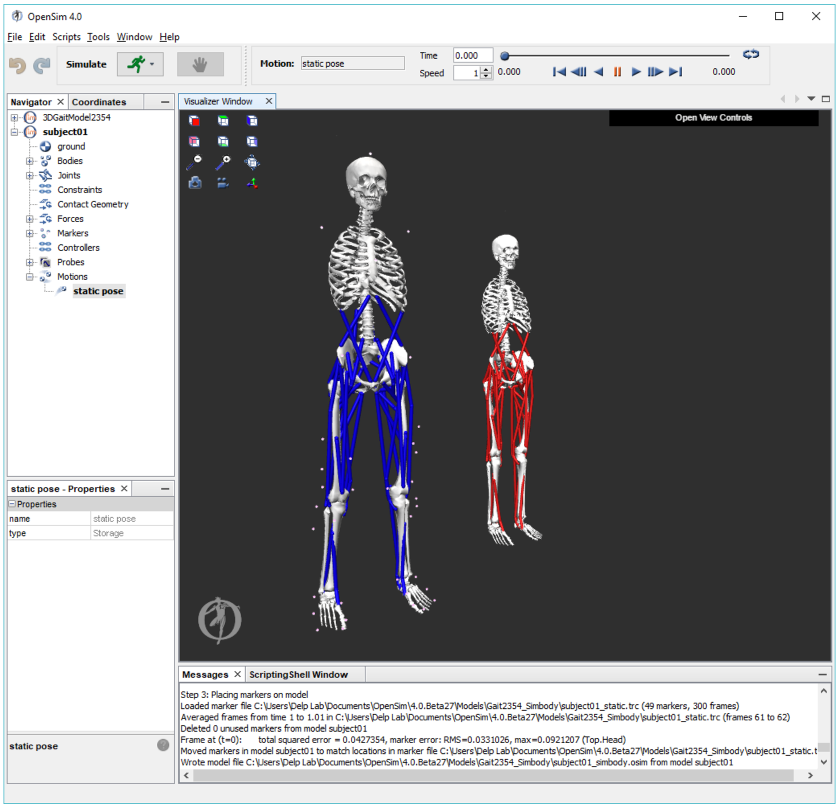



## Marker Registration

In OpenSim, the registration step adjusts the location of model markers to match the location of markers on the subject. To do this, you must first estimate a pose for the model that closely resembles the pose of the subject during the experimental static trial.

To complete the scale step:

- In the *Scale Tool* dialog, click **Run**.
- When complete, a new, scaled and registered model entitled *subject01* will appear in *Visualizer* window. Notice the pink model markers around the new model.
- To save the scaled model, either click **File** and select **Save Model,** or right-click on the model name, **subject01,** in the Navigator window, and select **Save As.**
- Save the scaled model as ***gait2354_scaled.osim***, and click **Save**. *Note: ensure that you are in the Gait2354 folder.*
- Once you have answered Questions 1-5, below, close the Scale Tool Dialog by clicking **Close**. At this point, you may close the generic model (right-click the model name in the Navigator window, and select **Close**) or hide the model (right-click the model name, and select **Display** -> **Hide**).




**Questions**

1. Based on information in the Scale Tool dialog, what is the mass of the generic musculoskeletal model? What was the mass of the subject?

2. What frequency was the experimental motion data captured?
*Hint: Look for the box titled Marker Data.*

3. Click on the **Scale Factors** tab. Which body segments were scaled manually?

# IV. Inverse Kinematics

*Kinematics* is the study of motion without considering the forces and moments that produce that motion. The purpose of inverse kinematics (IK) is to estimate the joint angles of a particular subject from experimental data. In this section, you will estimate a subject's joint angles during walking by performing an IK analysis using the subject scaled model and experimentally collected walking data.

For each time step of recorded motion data, IK computes a set of joint angles that put the model in a configuration that "best matches" the experimental kinematics. OpenSim determines this "best match" by solving a weighted least squares optimization problem with the goal of minimizing *marker error. Marker error* is defined as the distance between an *experimental marker* and the corresponding *model marker*. Each marker has an associated weighting value, specifying how strongly that marker's error term should be minimized in the least squares problem. For each time step, the inverse kinematics tool solves for a vector of generalized coordinates (e.g., joint angles), **q**, that minimizes the weighted sum of marker errors, which is expressed as

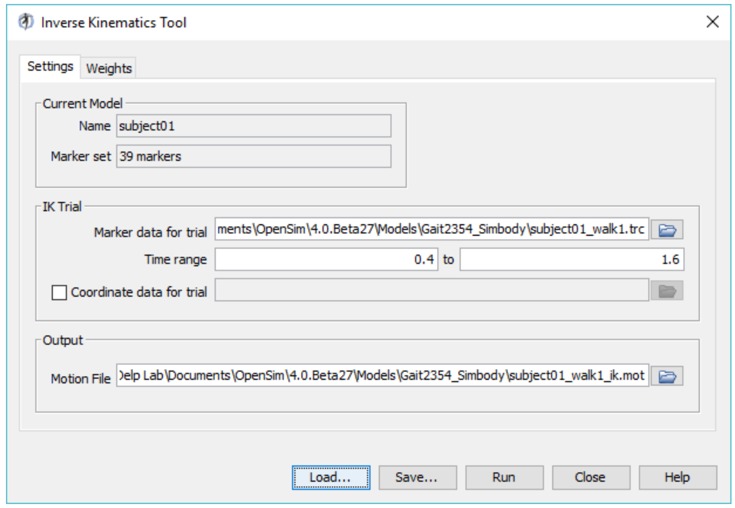
$$\min_{q}\left[\sum_{i\in \text{markers}} w_i \left\|\mathbf{x}_i^{\text{exp}} - \mathbf{x}_i(\mathbf{q})\right\|^2\right]$$

where **q** is the vector of generalized coordinates (e.g., joint angles), $\mathbf{x}_i^{\mathbf{exp}}$ is the position of *experimental marker i*, $\mathbf{x}_i(\mathbf{q})$ is the position of the corresponding *model marker i* (which depends on **q**), and $w_i$ is the weight associated with marker *i*.

To set up an inverse kinematics analysis:

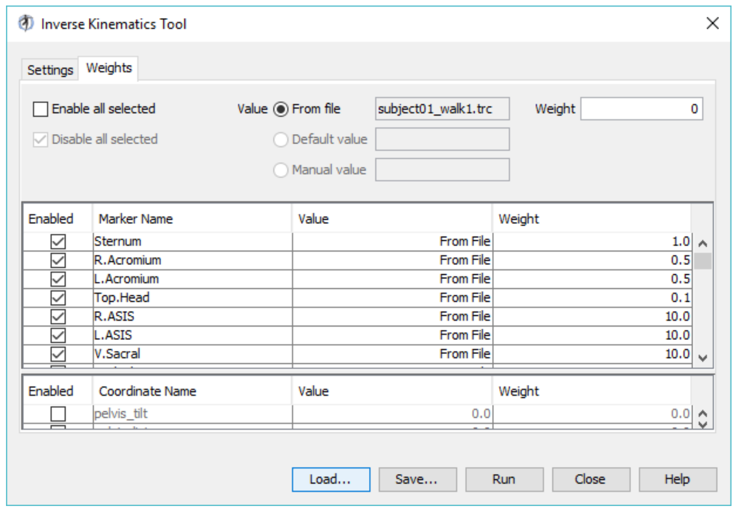
- Open the Inverse Kinematics Tool dialog window by clicking the **Tools** menu and selecting **Inverse Kinematics**.
- Load an inverse kinematics tool setup file by clicking **Load,** selecting the file ***subject01_Setup_IK.xml,*** and clicking **Open.**
  *Note: In the file browser, ensure that you are in the **Gait2354_Simbody** folder,*

subject01_Setup_IK.xml contains pre-configured settings for the inverse kinematics tool. Notice the text boxes in the dialog window are now filled with values. A detailed explanation of the Inverse Kinematics Tool can be found on the Inverse Kinematics page of the documentation.



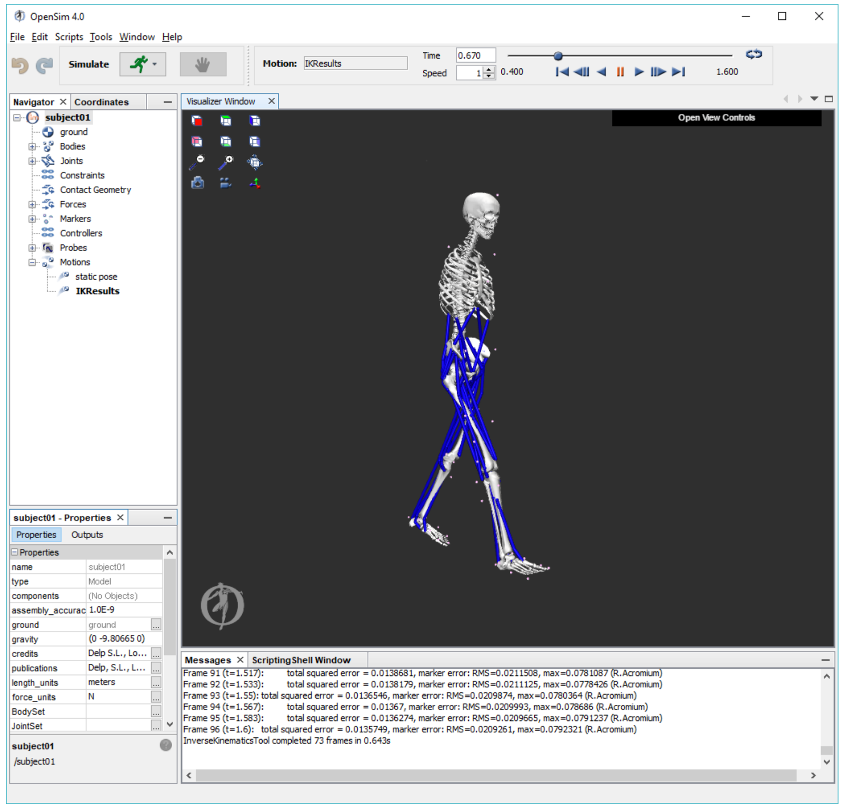

Navigate to the **Weights** tab.

- View which markers are selected for use in the inverse kinematics analysis, and their corresponding weights.
- **Enable** the tracking for the marker **R.Knee.Lat**. Notice the row turns red and the **Run** button is now greyed out. You will be unable to run the inverse kinematics tool because there is no experimental data found for the R.Knee.Lat marker in the **subject_walk1.trc** file. Disable the R.Knee.Lat marker and notice the **Run** button is now clickable.



To perform inverse kinematics:

- Click **Run.** The model will begin to move as the inverse kinematics problem is being solved for each frame of the experimental data.
- Notice the progress bar in the lower right-hand corner of the program. Wait until the bar disappears before proceeding.
  *Note: Closing the inverse kinematics tool dialog during the analysis doesn't affect the Inverse Kinematics tool running.*
- To visualize the inverse kinematics solution, animate the model by using the *motion slider* and *vi deo controls*. The model should walk through one full gait cycle.
  *Note*: *You can* ***loop*** *and control the speed of the animation.*
- The inverse kinematics solution is saved to *subject 01_walk1_ik.mot,* as specified in the setup file.
  *Note: Be sure to use the exact file name given, as this file is used later.*
- To compare experimental marker data with inverse kinematics results, in the *Navigator* panel, go to **Mo tions** and right-click on **IKResults** (which are what the Inverse Kinematics Tool just generated). Then choose **Associate Motion Data...** from the drop-down menu. Choose *subject01_walk1.trc* and click **Open**. *Model markers* are shown in pink and *experi mental markers* are shown in blue. Hit play in the Motion Toolbar. The *virtual markers* should correspond closely to the *experimental marker* loca tions as the animation proceeds.
- Click the **Window** menu and select **Messages.** Th e *Messages* window records details of all steps you have performed. Take a minute to explore the Messages window. Then, **scroll** to the very bottom. The line above *InverseKinematicsTool completed...* provides the markers errors and model coordinate errors (e.g., joint angle errors) associated with the last frame of the motion.
  *Note: All marker errors have units in meters, and all coordinate errors have units in radians*.
- Once you have answered Questions 4-6, below, close the Inverse Kinematics Tool Dialog by clicking **Close**.




**Questions**

4. In the Inverse Kinematics Tool dialog window, click the **Weights** tab and scroll through the list of markers in the top half of the weights tab. *Which markers have weighting values less than one? Why?*
*Hint: Think about joints that have not been modeled*.

5. *Based on information in the Messages window, what is the root-mean-squared (RMS) error of all the markers in the last frame of the motion? Include units. Does this seem reasonable? Explain.*

6. *What was the value of the maximum marker error in the last frame? Include units. Which marker had this maximum error, and why?*
*Hint: Think about the weighted least squares problem.*

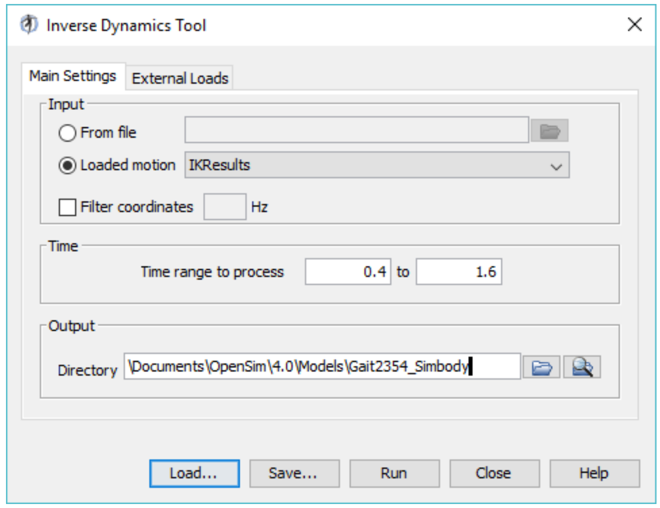
# V. Inverse Dynamics

*Dynamics* is the study of motion *and* the forces and moments that produce that motion. To perform inverse dynamics, estimation of mass and inertia is required. The purpose of inverse dynamics is to estimate the forces and moments that cause a particular motion, and its results can be used to infer how muscles are utilized in that motion. To determine these forces and moments, equations of motion for the system are solved iteratively [3]. The equations of motion are derived using the kinematic description and mass properties of a musculoskeletal model. Then, using the joint angles from inverse kinematics and experimental ground reaction force data, the net reaction forces and net moments at each of the joints are calculated such that the dynamic equilibrium conditions and boundary conditions are satisfied [3].

To setup an inverse dynamics analysis:

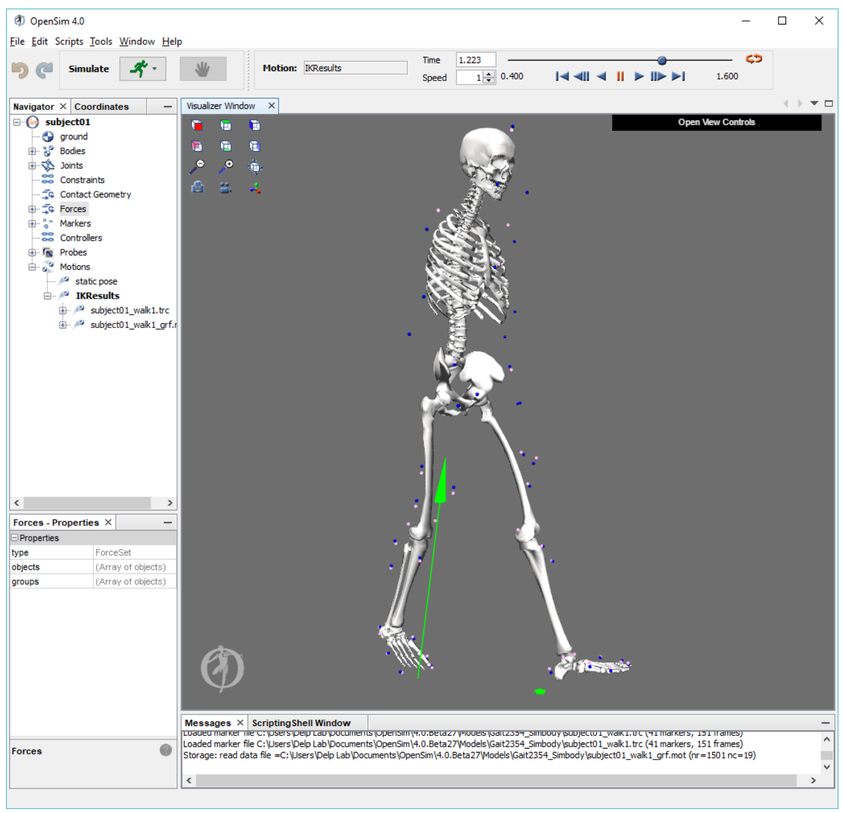
- Open the inverse dynamics tool dialog window by clicking the **Tools** menu and selecting **Inverse Dynamics**.
- Load an inverse dynamics tool setup file by clicking **Load,** selecting file ***subject01_Setup_InverseDynamics.xml,*** and clicking **Open.** *Note: If the **Motion From File** textbox appears red, this means the textbox was filled with an inappropriate file name. Make sure the motion file was saved with the correct file name in the Inverse Kinematics section.*
- Note the folder listed in the **Directory** textbox, located in the **Output** section of the dialog. The storage file containing the inverse dynamics results will be saved in this folder: *Documents\Opensim\Models\Gait2354\ResultsInverseDynamics.*

A detailed explanation of the Inverse Dynamics Tool can be found on the Inverse Dynamics page of the documentation.



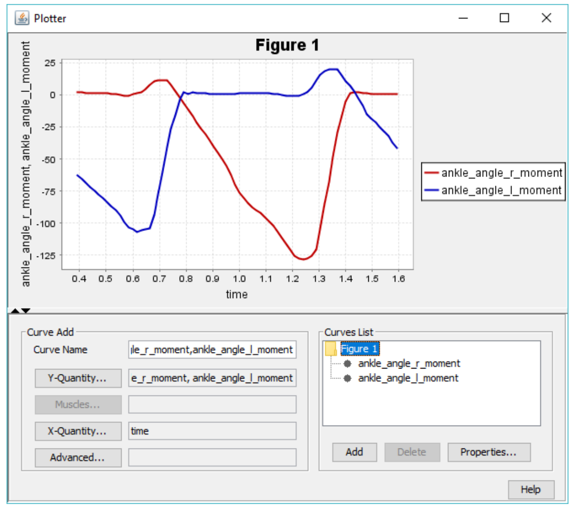

To perform inverse dynamics:

- Click **Run.**
- Notice the progress bar in the lower right-hand corner of the program. Wait until the bar disappears before proceeding. *Note: Closing the inverse dynamics tool dialog during the analysis doesn't affect the Inverse Dynamics tool running.*
- To visualize the inverse dynamics solution, animate the model by using the *motion slider* and *video controls*. The model should walk through one full gait cycle. *Note*: *You can **loop** and control the speed of the animation.*
- It is often useful to view the ground reaction forces with the inverse dynamics results. in the *Navigator* panel, go to **Motions** and right-click on **IDResults** ( which are what the Inverse Dynamics Tool). Then choose **Associate Motion Data...** from the drop-down menu. Choose *subject01_walk1_grf.mot* and click **Open**. Green arrows are now shown that represent ground reaction force vectors collected from a force plate.
- **Close** the inverse dynamics tool dialog window.



When completed, examine the results of the inverse dynamics solution by plotting the net moments at the left and right ankles:

- Click **Tools** and select **Plot**.
- In the *Plotter* window, click the **Y-Quantity** button and select **Load File**.
- In the file browser, go to the *ResultsInverseDynamics* folder, select the file ***inverse_dynamics.sto***, and click **Open**.
- In the menu, select **ankle_angle_r_moment** and **ankle_angle_l_moment** by clicking the corresponding checkboxes, then click **OK**.
  *Note*: To quickly find these quantities, type ankle into the pattern text box.
- Click the **X-Quantity** button, select **time**, and click **OK**.
- Back in the *Plotter* window, click **Add** to add the moment curves to the plot.
- Print your plot by **right-clicking** on the plot and selecting **Print**.
  *Note: To export the plot as an image by **right-clicking** the plot and selecting **Export Image**.*
- After printing the plot and answering questions 7-8, **Close** the *Plotter* and inverse dynamics dialog window



In solving the inverse dynamics problem, both kinematic data *and* force plate data were used, making this an over-determined problem. In other words, the problem has more equations than unknowns (i.e., degrees of freedom). Due to errors in the experimental motion data and inaccuracies in the musculoskeletal model, it turns out that Newton's second law is violated, or $\vec{F}_{\exp} \neq m \cdot \vec{a}$ [3]. One method to handle this inconsistency is to compute and apply residual forces and moments to a particular body segment in the model, such that Newton's second law becomes:

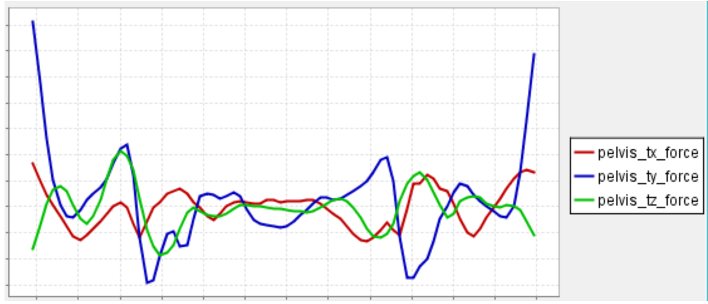
$$\vec{F}_{\exp} + \vec{F}_{residual} = m \cdot \vec{a}^{\dagger}$$

*† An analogous equation relates the ground reaction moment,* $\vec{M}_{\exp}$ *to the residual moment,* $\vec{M}_{residual}$.

In this musculoskeletal model, the residuals are applied to the pelvis segment.

To see the residuals from the inverse dynamics solution, in a new plot window, **Plot** pelvis_tx_force, pelvis_ty_force, and pelvis_tz_force versus time. Using this plot, answer question 9.

While applying residual forces and moments makes the model's motion dynamically consistent with the external forces $(\text{i.e., } \vec{F} = m \cdot \vec{a})$, this strategy is undesirable because the residuals can be large. More advanced strategies have been developed to deal with the problem of residuals and dynamic inconsistencies, such as least-squares optimization [3], the Residual Elimination Algorithm (REA) [5], and the Residual Reduction Algorithm (RRA) [6]. OpenSim implements a Residual Reduction Algorithm as part of its workflow for generating muscle-actuated simulations [6]. A detailed explanation of the Residual Reduction Algorithm (RRA) can be found on the Residual Reduction Algorithm page of the documentation. For additional information on these strategies, please also see [3], [5], [6], and [7].




## Questions

7. *On your plot of the ankle moments, identify when heel strike, stance phase, toe off, and swing phase occur for each curve (i.e., left leg and right leg).*

8. *Based on your plot and the angle convention for the ankle, give an explanation of what is happening at the ankle just before toe-off.*
*Hint: It may be useful to use the Coordinate sliders to understand the angle convention for the ankle*.

9. *What are the maximum magnitudes of the residual forces? Using the mass of the subject from Question 1, what fraction of body weight are the maximum residual forces?*

## Acknowledgments


The experimental gait data were collected by Jill Higginson and Chand John in the Neuromuscular Biomechanics Lab at the University of Delaware [8]. The data include marker trajectories and ground reaction forces for an adult male walking at a self-selected speed on an instrumented split-belt treadmill. Please note that the data distributed with OpenSim is from a different subject than the one described in the paper. Data collection protocols were the same for both subjects.


## References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8. Chand T. John, Frank C. Anderson, Jill S. Higginson & Scott L. Delp (2012): Stabilisation of walking by intrinsic muscle properties revealed in a three-dimensional muscle-driven simulation, Computer Methods in Biomechanics and Biomedical Engineering.