Simulation-Based Design to Prevent Ankle Injuries

All example files are included in the Model folder "ToyDropLandingModel" included with the OpenSim installation.

Overview

The purpose of this exercise is to use OpenSim to evaluate the risk of injury during landing and to design assistive devices to prevent injuries. You will examine how a passive ankle–foot orthosis (AFO), muscle reflexes, and muscle co-activation affect ankle inversion injury risk. In a short amount of time, you should be comfortable running forward dynamic simulations with varying conditions (such as orthosis stiffness) and plotting the results to compare their effects.

I. Explore the musculoskeletal model
II. Evaluate ankle inversion injury during a drop landing on a sloped surface
III. Analyze the effects of an ankle–foot orthosis (AFO) on ankle inversion
IV. Advanced Design Challenge: Create an active orthotic
V. Analyze the effects of muscle co-activation
VI. Explore: Prevent injury with a device and training program

Note that the musculoskeletal model and controller used in this example are simplified for demonstration purposes. A more comprehensive musculoskeletal model would be needed to perform research. For example, the controller is a simplified (toy) version of the stretch reflex generated by muscle spindles that detect lengthening of muscle fibers. The toy reflex controller responds to whole muscle–tendon lengthening speed and is not isolated to lengthening speed of the muscle fiber. Additionally, there is no transmission delay between stretch detection and eliciting a muscle excitation, and the model does not include all the passive structures (e.g., ligaments) that resist motion of the ankle joint.

Introductory Slides

I. Explore the musculoskeletal model

A. Launch OpenSim

You can launch OpenSim 3.2 from the Windows Start Screen (pre Windows 8, use the start menu). If you used default installation settings, simply select **Start Screen (Windows Key)** and type **OpenSim**. You will see multiple information panels and an empty main view.

B. Explore the model

1. In your favorite file browser, navigate to the folder where you installed OpenSim (e.g. C:\OpenSim 3.1), then find the folder **Models\ToyDropLanding**.
2. **Copy** the **ToyDropLanding** folder to a location of your choice. This well let you play with the models without fear of corrupting the example for future reference. From now on, we will refer to this location as **[Example_Dir]\ToyDropLanding**
3. In the OpenSim GUI, select **File>Open Model...**.
4. Select **ToyLandingModel.osim**.

The OpenSim GUI will now show a view window containing a model with a skeleton and a platform.

- The skeleton consists of a torso, a pelvis, and two legs with a total of 23 degrees of freedom and 70 muscle–tendon actuators.
- We can explore various components of the model using the **Navigator** panel. Expand the model by clicking the "+" icon next to the model's name. You should see groups including **Bodies** and **Joints**.
- Motion between the tibia and foot is described by two joints. Expanding the **Joints** group will reveal all joints in the model. Find the joints associated with the ankle of the right leg: **ankle_r** and **subtalar_r**. These represent the talocrural (or "true ankle") joint and the subtalar joint.
- Contact spheres are attached to the feet to produce foot–floor contact forces (see the **Forces>Contact Forces** group in the **Navigator** panel).

C. Explore the model's joint coordinates

The floor is modeled as a contact plane with four degrees of freedom. The model is posed so it will land on its right leg upon contact with the platform. The left hip and knee joints are locked to hold the pose and avoid interference from the left leg during landing. You can explore these degrees of freedom using the **Coordinates** panel:

1. Select the **Coordinates** tab in the left panel.
2. Use the sliders to change the **ankle_angle_r** and **subtalar_angle_r** coordinates. **Zoom in** on the ankle joint. Click and drag with the right mouse button to zoom in and out. Use the middle mouse button to translate and the left mouse button to rotate the view.
3. Unlock the **platform_rx** coordinate (by clicking on the lock icon).
4. Enter values in the **platform_rx** text field or move the slider to change the angle of the platform in the frontal plane. You can use the **platform_ry** and **platform_rz** coordinates to rotate the platform around its other two (orthogonal) axes.
5. Unlock **platform_ty** and change its value to move the platform up and down.
6. Select **Poses>Default** from the **Coordinates** panel to return the model to its original pose.
7. **Lock** all the platform coordinates.

Questions

1. Which degrees of freedom enable ankle inversion/eversion?
2. To tilt the platform in the sagittal plane (i.e. about the axis perpendicular to the sagittal plane), would you change platform_ry or platform_rz?
3. Why do you think the mtp_angle_r coordinate in the model is locked?

II. Evaluate ankle inversion injury during a drop landing on a sloped surface

A. Simulate a drop landing

1. Verify that the model is in its Default pose, with **platform_rx** set to 20 degrees, **platform_ry** to 0 degrees, **platform_rz** to 0 degrees, and **platform_ty** to -0.5 meters. All four platform coordinates should be **locked**. This will prevent the platform from falling or rotating on impact.
2. Find the **Simulate** button (Green Runner) in the OpenSim Toolbar.
3. Click the arrow next to the simulate button, and select the **End Time...** drop down item.
4. In the popup dialogue, set the simulation time to **0.4 seconds**. From now on, OpenSim will remember this choice when you hit the Simulate button and run a forward simulation for 0.4 seconds.
5. Click the **Simulate** button to simulate for 0.4 seconds. OpenSim will use the current pose of the model in the GUI as the starting state for the simulation. The model will animate during the forward simulation.
6. Once the simulation has completed, you can use the animation controls above the view window to play, pause, and scroll through the resulting motion and muscle activity. **Zoom in** on the ankle joint and **replay** the motion.
7. Click on the **Navigator** panel and find the **Motions** list. The motion Results in bold corresponds to the simulation you just generated.
8. **Right click** the bold "Results" motion and **Rename...** it to "Unassisted".
9. To save the results, **right click** the "Unassisted" motion and select **Save As** (e.g Results_Unassisted.sto).

B. Plot and analyze the simulation results

1. Open a new plot window by selecting **Tools>Plot...**.
2. Click the **Y-Quantity...** button and select **Unassisted(Deg.)...** near the bottom of the list to select kinematic data from your last simulation. If you saved the motion to a file, you can also use the **Load file...** option and navigate to the desired results file.
3. In the **Filter by pattern** text box, type "sub" to filter the results to just those containing the text string "sub".
4. Select **subtalar_angle_r** and click **OK**.
5. Select **X-Quantity>time** to choose time as the independent variable.
6. Click **Add** to display the data as a curve.
7. Click on "**Figure 1**" in the Curves List to highlight it. Click again to rename. Modify the title field (e.g., "Ankle inversion (subtalar angle) during drop landing"). Alternatively, right click and edit using in the **Properties** menu

8. Click on "**subtalar_angle_r**" to highlight the curve label in the **Curves List** box and click again to rename. Since this simulation used a model with no assistive devices, change this curve name to "Unassisted".
9. Answer the questions below, then **minimize** the plot window. Keep the plot window open so you can use it to compare these results to simulations with an AFO.

Questions

1. What is the maximum subtalar angle during the drop landing?
2. Would an ankle inversion injury have occurred during this landing? According to previous research (Siegler et al., 1990; Lapointe et al., 1997), angles larger than 25 degrees may cause injury.

III. Analyze the effects of an ankle–foot orthosis (AFO) on ankle inversion

You will now repeat Part II using a model with a two-segment passive ankle foot orthosis (AFO):

- The AFO has a footplate that is rigidly attached to the foot and a cuff that is rigidly attached to the tibia.
- The footplate and cuff are connected at two hinge points by six dimensional springs, called bushings. Pink markers identify the connection points. The bushings resist the relative translation and rotation of the footplate and cuff.

A. Explore the AFO model

1. Select **File>Open Model...** and select **ToyLandingModel_AFO.osim**. Once the model loads, you will see a similar drop-landing model, but with an ankle–foot orthosis (AFO) attached to the right foot. The model will also appear in the Navigator panel. It's name is in bold, indicating it is the current model.
2. Explore the model using the **Navigator** panel. Which new bodies and joints define the AFO we've added?
3. Find the **Property Editor** to see more details about these new components. If you don't see the Property Editor in the bottom-left corner of your screen, select **Properties** from the **Window** menu to display it.

B. Simulate and analyze a drop landing with a "soft" AFO

Simulate the drop landing with the default "soft" AFO:

1. Repeat the simulation steps from Part II.A above. The Simulate button acts on the current model, shown in bold in the Navigator panel. This should be the ToyLandingModel_AFO that you just loaded. Rename and the new results as "SoftAFO" this time and save as "Results_SoftAFO".

2. Repeat the plotting steps from Part II.B above. This time, instead of opening a new plot window, re-open the plot from Part II to add a new curve. Rename the new data curve from "subtalar_angle_r" to "Soft AFO". Minimize the plot window. (Don't close, since we'll add another curve).

C. Simulate and analyze a drop landing with a "stiff" AFO

Now let's try making the AFO stiffer. You can edit the properties of the AFO using the OpenSim GUI's Property Editor.

1. In the **Navigator** panel, go to **Forces**>**Other Forces** to find the **AFO_med_bushing**.
2. Highlight the **AFO_med_bushing** by clicking on it once. You should now see the properties of the AFO_med_bushing in the Property Editor.
3. Find the property in the list called **translational_stiffness**. This property controls the stiffness of the bushing that prevents the AFO cuff from translating with respect to the footplate on the medial side of the brace.
4. Make the translational_stiffness 10 times stiffer in each direction (i.e., set the translational_stiffness property to 100000 100000 100000).
5. Repeat steps 2–4 for **AFO_lat_bushing**.
6. Repeat the simulation steps from Part II.A one more time. Rename/Save the new results as "StiffAFO" this time.
7. Repeat the plotting steps from Part II.B. Once again, instead of opening a new plot window, re-open the plot from Part II to add a new curve. Rename the new data curve from "subtalar_angle_r" to "Stiff AFO".

Questions

1. You have now simulated three different drop-landing conditions: without an AFO, with a soft AFO, and with a stiffer AFO. What differences in peak ankle inversion do you observe between the simulations?
2. Could this AFO mitigate ankle inversion injuries?

IV. Advanced Design Challenge: Create an active orthotic

Rehabilitation robotics are providing new active devices to help train and optimize movement. Orthotics for ankle injury prevention have traditionally been passive devices, but what if you could create an active mode for landing? We will add a torque motor at the ankle to model an active orthotic. Your challenge will be to optimize the timing and activation level of the active orthotic to prevent ankle inversion injury.

A. Explore the AFO model

1. Download the Active AFO files (linked at the top of the page) and add unzip the contents to your folder, **[Example_Dir]\ToyDropLanding**
2. Select **File>Open Model...** navigate to the ToyDropLanding folder and select **ToyLandingModel_activeAFO.osim**.
3. Explore the model using the **Navigator** panel. What new forces have been added?

1. What degree of freedom does this motor control?
2. What is the optimal force of this motor?

B. Modify the active AFO torque profile

The default setting for the active AFO is 'off' and you will need to define when the orthotic is active. To specify the torque produced by the active AFO and run a forward simulation, we will use the Forward Tool, which allows specification of additional settings:

1. Select **Tools>Forward Dynamics...**. This launches the Forward Dynamics Tool.
2. Under the **Main Settings** tab, find the **Input** subsection.
3. Check the box for **Solve for equilibrium for actuator states**. This will initialize the tendon and muscle fibers before starting the integration.
4. Set the **Time range to process** as 0 to 0.4.
5. Change the output **Directory** by adding **\ActiveAFO** to the end of the displayed folder name. Depending on where you copied the example files, the location displayed should then be something like **[Example_Dir]\ToyDropLanding\ActiveAFO.**
6. In the Input Subsection, select the folder button next to Controls. Open the file **ActiveAFO_Controls.xml**.
7. Select the small pencil button next to the Controls box to edit this controls file. Under Select Excitations, check the box next to ActiveAFO and hit OK. This will open the Excitation Editor which shows the excitation of a controller (in our case, the activeAFO) with respect to time.
8. Change the excitation profile by moving the points in the Excitation Editor. To select a point, hold down CTRL and click on the point (similarly you can select multiple points by holding down CTRL and dragging the mouse over multiple points). To change the value of the points, you can either drag them on the screen, or enter a value in the "Set selected points to" box. You can also add or remove points. Click the "Help" button for more information.
9. Once you are done editing the excitation profile, select **Save As** to save an xml file called **ActiveAFO_Edited.xml.** Close the Excitation Editor.
10. On the Forward Dynamics set-up screen, make sure your edited Controls file is selected, by selecting the folder icon and choosing your new controls file.
11. You can save your settings to re-use later by clicking on the Save... button and saving your settings (e.g. setup_forward_activeAFO.xml).
12. Click **Run**. This will use the default options for all other settings. Since you haven't specified an Initial State file, the tool will use the current pose of the model in the GUI as the starting state for the simulation.
13. The model will animate during the forward simulation. You can **Close** the tool after you've clicked Run.
14. Once the simulation has completed, you can use the animation controls above the view window to view the motion.
15. Rename the new motion to "ActiveAFO". The results will be automatically saved by the forward tool in the directory you specified above ([Example_Dir]\ToyDropLanding\ActiveAFO).

C. Design optimal AFO for drop landing

Your challenge is to create the optimal AFO for drop landing. *Edit the activation of the AFO and the stiffness to optimize your design.* Your design will be judged on the following criteria:

- Minimal AFO stiffness (for maximum comfort and low material costs)
- Smallest torque required from the active AFO (for a small, compact motor)
- Minimal amount of time the AFO is active (to maximize battery life)
- Prevent ankle injury (inversion angle < 25°)

Note that you must start your simulation from the same initial conditions and posture used in the previous sections (no reducing the size of the drop or starting posture). Your final design will be "judged" using the following information: AFO stiffness, torque profile of active AFO, amount of time AFO is active, maximum torque of active AFO, and maximum ankle inversion angle.

V. Analyze the effects of muscle co-activation

Individuals can modulate the stiffness of the ankle by co-activating muscles in anticipation of landing. Thus, co-contraction of muscles, especially the inverter and everter muscles, might reduce ankle inversion during landing. The model comes equipped with two controllers that set the level of excitation (control) of the inverter and everter muscles. These controllers are initially disabled in the model. By enabling them you can explore the effect of increased muscle co-activity on ankle inversion during the drop-landing. The co-activation controllers will operate in addition to the reflex controllers in the model. The reflex controllers, which you saw in action in the previous simulations, activate based on the stretch of the whole muscle–tendon unit. The level of excitation of the muscle is proportional (via a gain) to the rate that the whole muscle actuator is lengthening.

A. Explore the model's controllers and simulate with co-activation

1. If the original unassisted **ToyLandingModel.osim** is still loaded, make it current by right-clicking on the model name in the **Navigator** panel and choosing **Make Current**. Make sure your model is in the **Default** pose (Coordinates>Poses>Default). If you closed the model, re-load it using **File>Open Model...**.
2. Go to the **Navigator** panel and find the list of the models **Controllers**.
3. Locate the **Reflexes** controller. What is the current value of the controller gain?
4. Find the co-activation controllers, **R-inverter controls** and **R-everter controls**. These controllers are disabled by default (i.e., the "isDisabled" property is true).
5. These controllers activate the specified muscles at a prescribed constant value throughout the simulation.To see the prescribed control values, highlight **R-inverter controls** or **R-everter controls** in the Navigator panel, then go to the Property Editor and click on the "**...**" button next to the "ControlFunctions" property. A tree view opens where you can navigate to the constants for each of the inverter or everter muscles in the model.
6. **Enable** the R-inverter and R-everter controls by unchecking the "isDisabled" property in each of these model components.
7. Run a forward simulation with the pre-activation controllers and add the results to your plot.

Questions

1. What is the constant control value for the inverters and everters when the co-activation controllers are enabled (see question 5 above)?
2. Does co-activity of the inverters and everters mitigate ankle inversion injury?
3. Optional: plot the muscle activations for the ankle inverters. How does the addition of the co-activation controller affect muscle activity?

VI. Explore: Prevent injury with a device and training program

In the sections above, you've explored how an AFO and muscle activation affect ankle inversion during landing. With the OpenSim simulation platform, there are many other scenarios and model properties that you can explore. For example, you can:

- Add a backpack to the model (by adding a new body or increasing torso mass)
- Change the initial pose of the model (e.g., increasing the initial ankle plantarflexion angle)
- Explore different device designs by changing stiffnesses or creating a new device
- Increase/decrease muscle strength to simulate training/disuse
- Change control strategies by altering the reflex gains, changing the amount of co-contraction, or adding new controllers
- Explore kinematics and loading at the other joints in the model during landing
- Test different landing scenarios (e.g., height, platform slope, surface characteristics)

Design Challenge

Apply what you've learned in the sections above to design an "optimal" device and training program to prevent ankle injury. You are free to modify any parameter of the model and the scenario, but keep in mind:

- Increasing the AFO's stiffness will increase manufacturing costs and decrease comfort and performance versatility.
- Training programs to increase muscle strength, improve co-activation strategy, improve landing position, etc. will also have costs.
- A device and training program that works in a variety of scenarios is ideal.
- Assume that a neutral ankle position (subtalar angle = 0) is ideal.

Develop a combined device and training program. Use simulation and your knowledge of biomechanics to demonstrate that your proposed solution is optimal.

Credits

Matt DeMers, Ajay Seth, Jen Hicks, Jeff Reinbolt, Ajay Seth with input and testing help from many others

References

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