Simulation 1:
Introduction to Musculoskeletal Modeling

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I. Objectives

SIMM (*Software for Interactive Musculoskeletal Modeling*) is a graphics-based software system that allows users to develop, alter, analyze, and visualize musculoskeletal models. In SIMM, a musculoskeletal model consists of a set of rigid body segments connected by joints and a set of muscles which span the joints. Once a musculoskeletal model is created, SIMM enables users to quantify the effects of musculoskeletal geometry, joint kinematics, and muscle-tendon properties on the forces and joint moments that the muscles can produce. SIMM is used at over sixty centers around the world in a wide variety of applications. Our goal is to provide a framework that will allow investigators to create a library of models that can be exchanged, tested, and multi-institutional collaboration.

Purpose of this Tutorial:
The purpose of this tutorial is to demonstrate the utility of graphics-based musculoskeletal models and to illustrate how muscle lengths and moment arms depend on limb position. By working through this tutorial, you will:

- become familiar with SIMM's viewing, plotting, and animation features
- discover some of the limitations of musculoskeletal models
- explore differences between 1-joint and 2-joint muscles
- use SIMM to address an actual clinical problem

Format of this Tutorial:
Each section of the tutorial asks you to execute a set of computer commands and answer a few questions. The computer commands which you must type to run SIMM and complete the tutorial are printed in **bold**. The questions can be answered based on what you observe using SIMM and on what you already know about the human musculoskeletal system. Use the blank answer sheet provided, which follows this tutorial. As you complete each section of the tutorial, feel free to explore SIMM and the lower extremity model further on your own.

II. A Musculoskeletal Model of the Lower Extremity

In this section of the tutorial you will load a model of the lower extremity into SIMM and make the model "walk". The model that you will use represents an adult subject with height ≈ 1.8 m and mass ≈ 75 kg. The model consists of 13 rigid body segments (pelvis and left/right femur, patella, tibia/fibula, talus, foot, and toes) and includes the lines of action of 86 muscles (43 per leg!).

Getting Started:

Start SIMM:

- Start SIMM by clicking on the SIMM icon on the Desktop. (It may say 'Shortcut to SIMM')

SIMM Basics:

Software Tools: When you start SIMM, a toolbar will appear along the top of the screen. In this tutorial you will use the File:Open, Model Viewer, and Plot Maker tools.

Mouse: Whenever an instruction is given pertaining to the mouse, it is assumed that you are using the left mouse button unless otherwise specified.

Exit Procedure: You may exit SIMM at any time by clicking on File:Exit. Before exiting, SIMM will ask you to confirm your action by clicking on *OK* to quit (or *Cancel* to continue).

If at any point in this tutorial you want more information about SIMM, you can find it in the SIMM users manual

Using File:Open:

The File:Open tool is used to load files that describe a musculoskeletal model or motion into SIMM. The first model you will analyze in this tutorial is entitled *Both Legs with Muscles.* Follow these steps to load the model:

- Click on File:Open. Change directories to the LegModel folder on the Desktop, select the file *bolegs.jnt* AND *bolegs. Msl* (using the CTRL key when you click the second one), and click on **Open**.

- Look at the SIMM Messages window. Notice that SIMM will notify you if it opened successfully.

- You may want to make the model window larger. Resize the window by clicking and dragging on a corner of the window.

- To animate the model, you will also need to load a motion file into SIMM. The file *bowalk.mot* describes a normal gait cycle. Click on File:Open, select the file *bowalk.mot*, and click on **Open**. This reads the motion file into SIMM and links it to the model.

You are finished with File:Open for now.

Using the Model Viewer:
The Model Viewer tool lets you change how you view a model. This section of the tutorial will introduce you to SIMM's viewing and animation features:

- Open the Model Viewer tool by clicking ‘Model Viewer’ on the toolbar at the top of the screen. You may need to make the Model Viewer window larger by clicking and dragging on its border.

- The right-hand side of the Model Viewer window contains a group of sliders. The first three sliders correspond to rotations of the model about the Z (out of the screen), X (horizontal), and Y (vertical) axes of a "world" reference frame. Rotate the model about each axis by dragging the corresponding slider horizontally.

- The left-hand side of the Model Viewer window contains a command menu. To return the model to its original position, click on **restore gc values** in the command menu.

- The rest of the sliders in the Model Viewer window (except the last) correspond to rotations of the body segments about the joints of the model. Each slider controls one degree of freedom. Move the joints by dragging the sliders horizontally. To return the model to its original position, click on **restore gc values**.

- The “gait_cycle” slider in the Model Viewer window (at the bottom of the list) corresponds to the motion file which you loaded into SIMM. To animate the model, drag this slider horizontally. You can also animate the model continuously by clicking on **start>** in the command menu and selecting ***gait_cycle*** from the pop-up menu. Notice how the sliders in the Model Viewer window move as the model "walks". Click on **stop** to stop the animation.

- SIMM also allows you to position the model using keyboard commands. To rotate the model about the X-axis of the world reference frame, place the cursor in the model window and press the ***CTRL*** key and the **left mouse** button. The direction and speed of rotation are determined by the position of the cursor in the model window. If the cursor is at the far right edge of the window, the model will rotate quickly in the positive direction about the X-axis. As you move the cursor left, toward the center of the window, the rate of rotation slows down. If the cursor is in the middle of the window, the rotation rate is zero. As you move the cursor further left, toward the left edge of the window, the rotation rate increases, but in the negative direction. Pressing the ***CTRL*** key and the **middle mouse** button, in a similar manner, rotates the entire model about the Y-axis. Pressing the ***CTRL*** key and the **right mouse** button rotates the model about the Z-axis. Experiment with these keyboard commands. To return the model to its original position, click on **restore camera->camera 1**. (You can save up to five camera views under **save camera** and then restore those corresponding views with **restore camera**).

- Additional keyboard commands allow you to zoom and pan. Click in the model window and try pressing the following keys:
  i — zooms the model in toward you, making it larger
  o — zooms the model out away from you, making it smaller
  l — pans the model to the left within the model window
  r — pans the model to the right within the model window
  u — pans the model up within the model window
  d — pans the model down within the model window

The speed with which the model moves depends on the current "gear". Use the gear slider to change the speed of the model.

- Now that you are familiar with SIMM's viewing commands you can watch the model "walk" from different angles. Use the keyboard commands to orient the model as desired. Then click on **start>** and select ***gait_cycle*** to begin the animation. To view the model from a different perspective simply stop the animation, reposition the model, then start the animation again. To return the model to its original position, click on **restore gc values**.

Exploration & Questions: Features and Limitations of Musculoskeletal Models
1. <u>Degrees of Freedom:</u>

a. Use the Model Viewer slider bars and the keyboard viewing commands to study the degrees of freedom of the model. How many degrees of freedom does the model have? Can you name them?

b. Compare the degrees of freedom in the model to the degrees of freedom in your lower limbs. Which motions have been simplified? Which motions haven't been modeled?

2. <u>Bone Surfaces:</u>
Bone surfaces are represented in SIMM by a mesh of planar polygons. To get a better view of the bones, you can "hide" the muscles from view:

- Click on the **muscles>** item in the command menu of the model viewer. A pop-up menu of muscle groups will appear. Select ***all*** from the pop-up menu.

- Now **scroll** to the bottom of the Model Viewer window where you will find a list of all the muscles in the model. You may need to enlarge the Model Viewer window to see the entire list.

- Click on the name of a muscle to toggle its display in the model window. Click on ***all*** (the title bar above the list) to toggle the display of all the muscles in the list.

a. Study the bones in the model. How realistic do they look?

b. Now **scroll** to the top of the Model Viewer window and click on **draw mode** in the command menu. A pop-up menu of objects will appear. Select ***all body segments*** from the first menu and ***wire frame*** from the second pop-up menu.

3. Muscle Paths:

Muscle-tendon paths are represented in SIMM by a series of points connected by line segments. To view the points which define the muscle-tendon paths:

- Bring the muscles back into view by clicking on ***all*** (the title bar above the list of muscles).

- You may also want to restore the bones to the ***flat shaded*** mode.

- Finally, click on the **muscle points** box beneath the gear slider to display (in the model window) all of the "muscle points" which define the muscle paths.

a. **Scroll** to the bottom of the Model Viewer window and examine the list of muscles. You will notice that some muscles are represented by multiple lines of action. Locate these muscles on the model. (To locate a muscle, toggle its display on and off by clicking on its name. You may want to expand the size of the window to see all the muscle names.) Why do you think these muscles are represented in this way?

b. For some muscles, just two points (the muscle's origin and insertion locations) are sufficient to describe the muscle's path. For other muscles which wrap over bones or are constrained by retinacula, intermediate "wrapping" points or "via" points must be defined. Zoom in on the right knee joint using the keyboard viewing commands. Flex the knee using the Model Viewer slider bars and observe the paths of the knee extensor muscles. Notice how wrapping points are introduced at certain knee angles such that the muscles appear to "wrap" around the bones. Which muscles are these? At what knee flexion angles do the wrapping points appear? (To identify these muscles, use the muscle menu to display a list of knee extensors. Go to the end of the muscle list (at the bottom of the window) and click on **<<done>>**. Then click on **muscles>** in the command menu and this time select ***knee_ext*** from the pop-up menu. A list of knee extensors will appear in the Model Viewer window. To locate a muscle, toggle its display on and off by clicking on its name. These muscles may be easier to see if you turn off all the other muscles. This can be done by selecting ***all off*** from the end of the muscle menu.)

4. Modeling Limitations:

Despite efforts to define muscle paths accurately using via points and wrapping points, some muscles in the lower limb model pass through the bones or deeper muscles at extreme ranges of motion. Click on **reset view** in the model viewer window. Zoom in on the right hip joint using the keyboard viewing commands and flex the hip using the Model Viewer slider bars. What do you observe? Check out the muscle GMAX3 for a range of hip flexion angles. Do you see any problems? In what ways are point-to-point representations of muscle paths a simplification of musculoskeletal geometry?

5. Utility of Computer Graphics:
The human musculoskeletal system is quite complex. Imagine trying to develop, analyze, or visualize a 3-D musculoskeletal model without the benefit of computer graphics. What does this suggest about the utility of computer graphics in biomechanics research?

III. Relationships Between Joint Angles, Muscle Lengths & Moment Arms

In this section of the tutorial you will investigate how muscle lengths and moment arms depend on limb position. But, you might wonder, isn't the primary function of muscles and tendons to actuate movement by developing and transmitting force to the skeleton? How important is this musculoskeletal geometry stuff anyhow?

As it turns out, musculoskeletal geometry is very important to the function of muscles and tendons, and it is particularly important to the development of quantitative musculoskeletal models. Since musculotendon forces depend on musculotendon length, and since joint moments depend on both musculotendon force and moment arm, accurate specification of musculoskeletal geometry is essential if muscle forces and joint moments are to be estimated. Further, because musculotendon lengths and moment arms depend upon limb position, muscle forces and joint moments also depend on limb position, but in a much more complex manner. Studying the relationships between joint angles, muscle lengths, and moment arms, then, may provide insight into the behavior of muscle forces and joint moments as well.

Using the Plot Maker
SIMM's Plot Maker tool allows you to plot muscle-tendon properties such as length, moment arm, force, and joint moment as a function of any joint angle or motion variable. Follow these steps to generate a plot of muscle fiber length vs. knee angle for the rectus femoris and vastus intermedius muscles:

- Return the model to its original position by clicking on **restore gc values**. In general, plots are created for the current limb position as displayed in the model window. Thus, the following plots will be generated for 0 degrees hip flexion, abduction, rotation, and ankle flexion until you re-position the model.

- Put the Model Viewer tool away by clicking on the “X” in the upper right corner.

- Open the Plot Maker tool by clicking on “Plot Maker” on the toolbar at the top of the main window.

- To select the muscles for which you want to generate plot curves, click on **muscles>** in the Plot Maker command menu. When you choose a muscle group from the pop-up menu, a list of the corresponding muscles is displayed at the bottom of the Plot Maker window. In this case, select ***knee_ext*** from the popup menu. **Scroll** to the bottom of the window (or make the window larger) and find the muscle list.

- Select rectus femoris and vastus intermedius from the list by clicking on **Rectus_Femoris** and **VASINT**.

- Return to the top of the Plot Maker window. Click on **y-variable** and select ***fiber length***. This is the variable which will appear on the "y-axis".

- Click on **x-variable** and select ***r_knee_angle***. This is the variable which will appear on the "x-axis".

- Finally, click on **make curves**. A plot window will appear showing the fiber length vs. knee angle curves for the selected muscles. The units in all plots are meters (length), Newtons (force), and Newton-meters (moments).

Exploration and Questions: Musculoskeletal Geometry

1. <u>Muscle Length vs. Joint Angle:</u>

   a. Study the plot of muscle fiber length vs. knee angle for rectus femoris and vastus intermedius. What do you observe? Do you think these curves would look different if, for example, the right hip was flexed?

   b. Now flex the right hip and regenerate the plot:

- Open the Model Viewer tool.

- Flex the right hip by 45° by typing **45** into the *r_hip_flexion* text box and press **Enter**.

- Close the Model Viewer.

- Go back to the Plot Maker window, click on **plot>**, and select ***new plot*** from the pop-up menu. This instructs SIMM to display the next plot in a new window.

- Finally, click on **make curves** to generate the plot for a hip flexion angle of 45°.

Carefully compare these curves to the previous ones. What do you observe? Can you explain your findings?

2. <u>Muscle Moment Arm vs. Joint Angle:</u>

Now plot knee extension moment arm vs. knee angle for the same two muscles:

- First delete the old plots. This can be done by either using the **delete curves** button in the Plot Maker window, or by positioning the cursor over a plot and using the backspace key on the keyboard. In either case, in order for the curves on a plot to be "deletable", the background of the curve name in the legend must be white. Use the mouse to toggle the legend background between black and white to control which curves to delete. (Make all of the curves white if to delete an entire plot.)

- Open the Model Viewer. Return the model to its original position by clicking on **restore gc values**, and close the Model Viewer.

- Click on **y-variable** in the Plot Maker window, select ***moment arm*** from the first pop-up menu, and select ***r_knee_angle*** from the second pop-up menu. The **x-variable** remains unchanged.

- Finally, generate the new curves by clicking on **make curves**.

a. Study the plot of knee extension moment arm vs. knee angle for rectus femoris and vastus intermedius. At what knee angles do the moment arms peak? What are the peak moment arms? What are the minimum moment arms? (Note that the coordinates of any point in a plot window can be obtained by clicking on that point. You can also zoom in on plots with the **i** key and out with the **o** key).

b. You may wonder about the discontinuity, or sharp point, which appears in these moment arm curves. At what knee angle does the discontinuity appear? What do you think causes the discontinuity? (Hint: Look at question II.3.b on page 5)

Although the knee extension moment arm curves for rectus femoris and vastus intermedius are similar, the moment arm curves for different muscles, in general, vary widely. To illustrate this point, plot hip flexion moment arm vs. hip flexion angle for sartorius, rectus femoris, iliacus, and tensor fasciae latae as follows:

- De-select vastus intermedius by clicking on **VASINT** in the knee extensor muscle list and close the list by clicking on <<**done**>>.

- Delete the previous plot.

- Click on **muscles>** and select ***hip_flex*** from the pop-up menu.

- Scroll to the bottom of the Plot Maker window and find the list of hip flexors. Select sartorius, tensor fasciae latae, and iliacus from the list by clicking on **SAR**, **TFL,** and **Iliacus**. Note that rectus femoris is still selected from the previous plot (if it is not, click on **Rectus_Femoris** in the *knee_ext* list as well).

- Click on **y-variable**, select ***moment arm*** from the first pop-up menu, and select ***r_hip_flexion*** from the second pop-up menu.

- Click on **x-variable** and select ***r_hip_flexion*** from the pop-up menu.

- Finally, click on **make curves**. A plot window will appear containing the moment arm curves for the four muscles.

c. Study the hip flexion moment arm vs. hip flexion angle curves for these muscles. What do you observe?

d. Now open the Model Viewer tool, and abduct the right hip by 15° by typing **-15** into the *r_hip_adduction* text box. (Note that a**b**duction is the opposite of a**d**duction.)

Return to the Plot Maker and click on **make curves**. Are the hip flexion moment arms of these muscles affected by the change in hip abduction angle?

Feel free to experiment with other limb positions, other muscles, and/or other joints. When you are ready to continue with the tutorial, delete old plot windows and close the Plot Maker. You may also want to delete the *Both Legs With Muscles* model from SIMM, since you won't be using it in the last section of the tutorial. To do this, place the cursor over the model and hit backspace.

IV. Assessment of Hamstrings Length During Crouch Gait

In this final section of the tutorial you will use SIMM to investigate a possible cause of crouch gait. Crouch gait is one of the most common walking abnormalities among persons with cerebral palsy. It is characterized by excessive flexion of the knee during the stance phase, which is often accompanied by exaggerated flexion, adduction, and internal rotation of the hip. One hypothesized cause of crouch gait is short hamstrings, and orthopaedic surgeons will sometimes lengthen the hamstrings of such patients in an attempt to improve their posture and/or gait. But, other causes of excessive knee flexion are possible (e.g. inadequate plantar flexion strength, short hip flexors, weak hip extensors ...), and lengthening the hamstrings can compromise the muscles' capacity to generate forces and joint moments, leaving some patients with weak or dysfunctional limbs. How can a surgeon determine whether a hamstrings lengthening procedure is warranted?

One way to judge whether a patient's hamstrings are shorter than "normal" might be to develop a musculoskeletal model and compare the length of the hamstrings over the patient’s crouch gait cycle to the length of the hamstrings over 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 or not to operate, and he wants your opinion.

File Preparation
Follow these steps to load the crouch gait files:

- Click on File:Open, select the file *seplegs.jnt* AND *seplegs.msl* (using the CTRL key when you click on the second one), and click on **Open**. Notice that SIMM opens a second window for this new model. This model is similar to *Both Legs With Muscles* except that it has a right pelvis segment and a left pelvis segment which connect separately to the sacrum.

- Click on File:Open, select the file *crouch1.mot*, and click on **Open** to read in a motion file containing crouch gait data.

- Click on File:Open, select the file *normal.mot*, and click on **Open** to read in a motion file containing normal gait data. Note that more than one motion file can be associated with the same SIMM model.

Exploration and Questions: Crouch Gait

1. Range of Motion:

   a. Animate the model and visually compare the crouch gait data to the normal gait data. That is, open the Model Viewer window and click on **start>**. Select ***crouch1_gait*** from the pop-up menu to view the crouch gait data or ***normal_gait*** to view the normal gait data. Increase the value in the **gear** field to make the animation move faster. Rotate the model and watch the motion in several planes. What do you observe?

   b. Now quantitatively compare knee flexion angles over the crouch gait and normal gait cycles. Open the Plot Maker tool and click on **motion curve>**. Select ***normal_gait*** from the first pop-up menu, select ***generalized_coordinates*** from the second pop-up menu, and select ***r_knee_angle*** from the third pop-up window. A plot of right knee flexion will be displayed vs. percent of gait cycle. Can you identify, for this curve, the intervals at which heel strike, stance, toe off, and swing phase occur? What is the "normal" range of knee flexion during stance?

   Click on **motion curve>** again. This time select ***crouch1_gait*** from the first pop-up menu, ***generalized_coordinates*** from the second pop-up menu, and select ***r_knee_angle*** from the third pop-up window. How does the knee flexion curve for the crouch data compare to "normal"?

2. Hamstrings Length:

To address the surgeon's question, compare the hamstrings length over the crouch gait cycle to the hamstrings length over the "normal" gait cycle:

- Delete the old plot window.
- Click on **muscles>** and select ***knee_bend*** from the pop-up menu.
- Scroll to the bottom of the Plot Maker window, find the list of knee flexors, and click on **hamstrings**.
- Click on **y-variable** and select ***musculotendon length*** from the pop-up menu.
- Click on **x-variable** and select ***normal_gait*** from the pop-up menu.
- Finally click on **make curves**. A plot of hamstrings length vs. percent of gait cycle will appear.
- To overlay a similar curve for the crouch gait data, click on **x-variable**, select ***crouch1_gait*** from the pop-up menu, and click again on **make curves**.

Study the curves. On the basis of this plot, what recommendation would you give the surgeon? Can you think of any limitations of this analysis?

3. 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/or *crouch4.mot*. Would your recommendation to the surgeon be any different for these patients?