Tutorial: Calculating Spine Loading with the Thoracolumbar Spine and Rib Cage Model

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I. <u>Objectives</u>

<u>Purpose:</u>

This tutorial explains how to use our male and female thoracolumbar spine models to estimate vertebral loading. Spine loading, in addition to vertebral strength, may be helpful to consider when estimating vertebral fracture risk[3]. OpenSim contains many computational tools to help calculate parameters needed to estimate spine loading. We will load predefined motion and external force files, run static optimization and joint reaction analysis, and then calculate spinal loading with custom MATLAB scripts. The schematic below (Figure 1) shows an overview of the vertebral loading estimation process from input motion and external force files.

In this tutorial, you will:

- Become familiar with our thoracolumbar spine models
- Use MATLAB to solve the model via static optimization and joint reaction analysis
- Calculate spinal loads from joint reaction analysis
- Plot compressive loads throughout the thoracolumbar spine
- Investigate how different postures influence spine loading

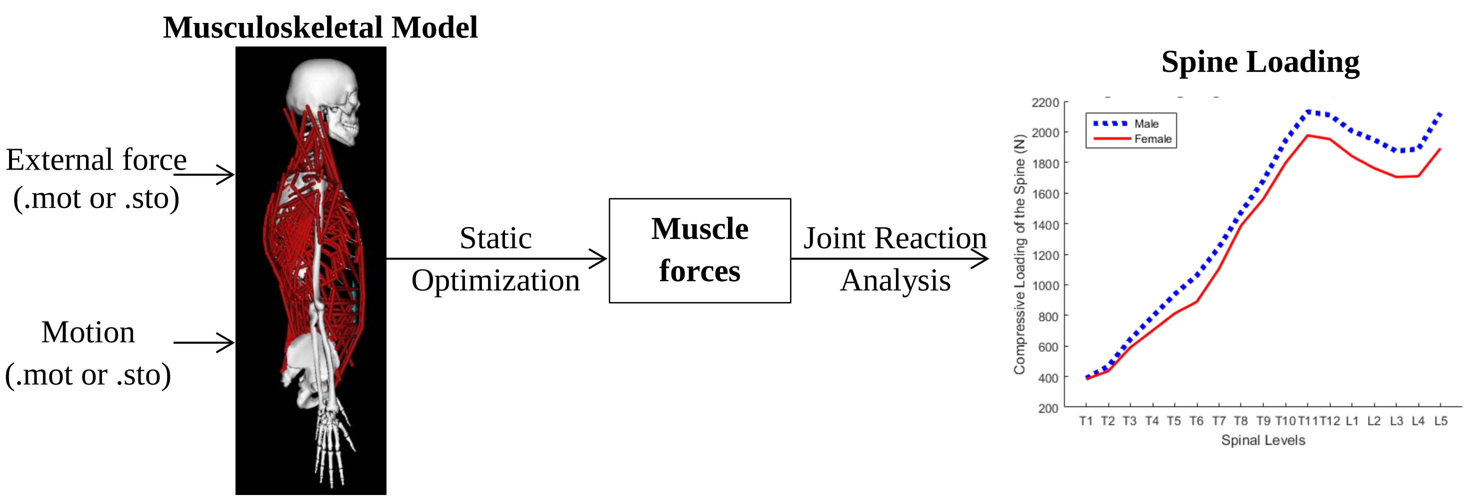

Figure 1: Schematic showing calculation of vertebral compressive loading with OpenSim thoracolumbar spine model

Format

Each section of the tutorial guides you through using certain MATLAB scripts. At the conclusion, the tutorial asks you to answer a few comprehension check questions. The questions can be answered based on information from OpenSim and basic knowledge of the human musculoskeletal system. Menu titles and variables that require editing within the MATLAB scripts/interface will appear in **bold face**. Script filenames will appear in *italics*. Depending on the amount of exploration you do, this tutorial should take less than 1 hour to complete.

II. **Setting Up and Running OpenSim Through the MATLAB Environment**

In this tutorial, we will be using our generic male and female thoracolumbar spine model actuated by 552 muscles (https://simtk.org/projects/spine_ribcage). Before running scripts with OpenSim, make sure that you have set up scripting with MATLAB (https://simtk-confluence.stanford.edu/display/OpenSim/Scripting+with+Matlab).

There are 4 different m files (MATLAB Files), 3 .xml set-up files, 4 motion files, and 4 external load files that can be found in the folder after unzipping:

- *Header_OpenSim.m*
- *Do_StatOpAnalysis.m*
- *Do_JntReactAnalysis.m*
- *Get_VertLoad.m*
- *extForces_Setup.xml*
- *jointReact_Setup.xml*
- *staticOpt_Setup.xml*
- *4 Motion files*
- *4 External load files*

1. Header_OpenSim.m

This file is the header file that executes all other MATLAB scripts below. The header file runs the model to obtain muscle forces, joint reaction loads, and final spinal loads assuming we provide relevant input motion and external load files.

Some updates need to be made to file directories before the script will run on your computer. The variable **FileDirectory** and **Models** must be updated, and the other variables can be optionally updated if you choose to run different activity files or change the results directory.

- **FileDirectory** (line 13): variable that points to the folder that contains the OpenSim model, analysis set-up files, motion and external load files.

- **Models** (line 18): this variable selects the model file name that will be used for this analysis
- **Activities** (line 20): Selected motion and external load file numbers that simulate different predefined quasi-static activities (Figure 2).

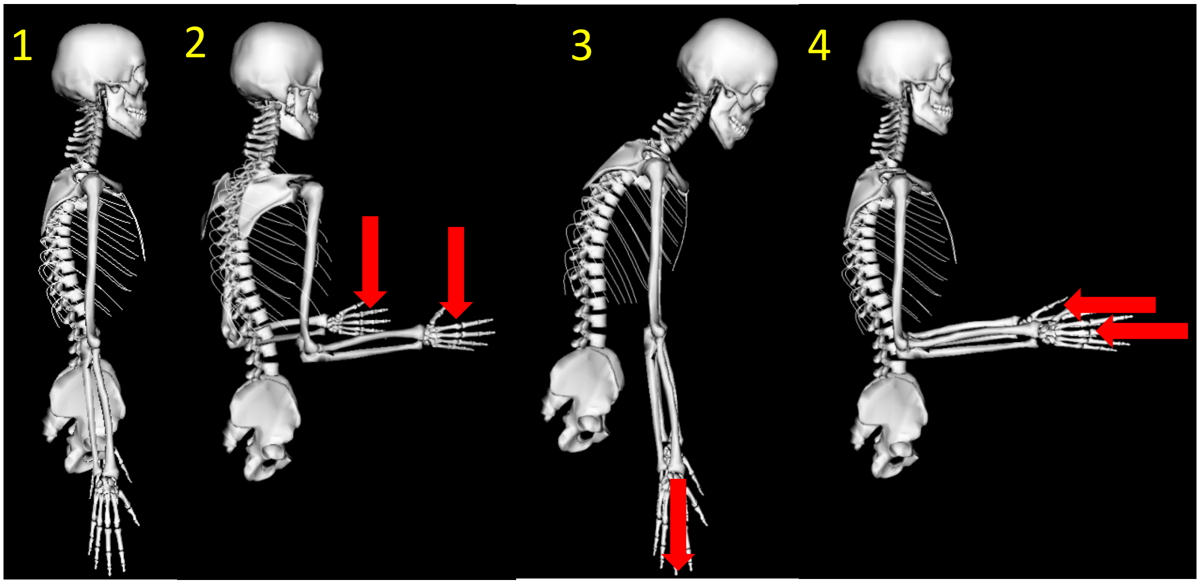

Figure 2: Sample activities 1-4 depicted in OpenSim with red arrows denoting direction of external force. Activity 1 – neutral standing, no external force. Activity 2 - 30˚ axial twist, elbows flexed 90˚, 10 kg of weight in each hand. Activity 3 - trunk flexion to 30˚ with 5 kg of weight in each hand. Activity 4 - elbows flexed 90˚, pushing forward against 50N force each hand (pushing a shopping cart).

- **TutorialDir** (line 48): this variable selects the folder in which analysis results will be placed.
- **Filename** (line 61): this variable names the excel output file with vertebral load results.

At the bottom of the header file, some example code is given to plot the results from the 4 example activities. This section of the header file is explained in more detail in part III of the tutorial.

Once these variables have been updated, the header file is ready to run. The scripts below are called by the header file and are described for your knowledge only.

2. Do_StatOpAnalysis.m

This file requires several inputs to run the static optimization as seen below:

Do_StatOpAnalysis(modelpath,motionpath,extloadpath,resultpath,FileDirectory)

All the inputs to this function are pre-filled in the header file step above (*Header_OpenSim.m*). To make changes or adapt it to your own purpose, please modify the header file as needed.

The objective of this script is to perform a static optimization in OpenSim using models, relevant motions and external loading files. This script will output 4 result files to the **TutorialDir** location (*NMB_StaticOptimization_activation.sto*, *NMB_StaticOptimization_controls.xml*, *NMB_StaticOptimization_forces.sto*, and *staticOpt_Setup.xml*). These files will be called by the scripts below.

The activities in this tutorial should have their static optimizations solve successfully. However, it's important to note that even when static optimization fails, data is still placed in result files. To investigate if a static optimization failed, look at the out.log file that was generated in the **FileDirectory** after running the static optimization function.

Note: Make sure setup files for external loading and static optimization are contained in the same file directory as the MATLAB scripts. These files are available in the downloaded folder.

3. Do_JntReactAnalysis.m

This function updates the joint reaction setup file (*jointReact_Setup.xml*) based on the input in *Header_OpenSim.m* and runs the joint reaction analysis following static optimization in OpenSim. The outcome of this file provides joint reaction forces in 3 anatomical planes (Anterior-Posterior (AP), Medio-Lateral (ML) and Superior-Inferior (SI)). This script will output 6 result files to the **TutorialDir** location, including *jointReact_Setup.xml*, an *NMB_ForceReporter_forces.sto* file, and 4 *NMB_JointReaction* files. These files will be called by the *Get_VertLoad.m* script.

4. Get_VertLoad.m

After running static optimization and joint reaction force analyses, this function is called to collect joint reaction forces in all anatomical planes (AP, ML, and SI) and calculate spinal loading in AP shear, ML shear, and SI compression. The vertebral loads are calculated for the mid-vertebral body as an average of the superior and inferior joint loads. Compressive spine loading has been validated[1], however AP and ML shear loads have not been validated.

The spine loading results are stored in an Excel file named by the **filename** variable. The spine loading file is organized with a tab for each loading direction (named by the strings in lines 62-64). The file contains spine loads in Newtons (N) in columns A through Q, which correspond to vertebral levels T1 through L5.

The modeling approaches above were used to calculate spine loading in our publications[1-3].

III. Plotting Spine Loading Results

The bottom of the *Header_OpenSim.m* file contains example code to plot the 4 sample activities for a given model. All variables used have already been defined above, and code can be run as-is without modification.

The first loop of the section compiles spine loading results from Excel files into MATLAB variables. The next loops plot spine compressive load, AP shear, and ML shear respectively. The AP and ML shear plots are commented out by default. These plots will show all 4 activities in a subplot, however be sure to notice that the y-axis scale may not be the same between activities.

IV. Questions

1. Compressive Spine Loads

a. At what location (vertebral level) of the thoracolumbar spine do you observe the largest compressive load for the 'Standing' activity? What location do you observe the second largest load? Is this the same across different activities? *Notice that while general patterns may be similar across some activities, magnitude and curve shape typically vary between modeled activities. This demonstrates the importance of modeling your unique activity to estimate spine loading.*

b. What percentage of body weight is being applied to the spine in each activity? For reference, the male thoracolumbar spine model has a weight of 78 kg and the female thoracolumbar spine model has a weight of 72 kg.

c. Compare spine loading results between the male and female thoracolumbar spine models. What differences do you observe in compressive spine loading between male and female spine models?

d. Using the provided motion and external force files, try running the 30 degrees trunk flexion posture (Motion 3) with 10kg per hand external force (External force 2), instead of 5 kg per hand. What if no external forces are applied? Compare how vertebral compressive loading changes with different weights applied.

2. Shear Forces

Our AP and ML shear forces haven't been validated, but you can optionally investigate these forces across the spine as well by uncommenting the last 2 plots in the *Header_OpenSim.m* script.

Well done! If you are here and have done all the steps correctly, you have completed the tutorial for thoracolumbar spine and rib cage model in OpenSim. You notice how much load our spine can withstand, so take care of your back and spread the word.

Please cite the following papers in future studies after using the model and this tutorial.

References:

1. Bruno AG, Bouxsein ML, Anderson DE. Development and Validation of a Musculoskeletal Model of the Fully Articulated Thoracolumbar Spine and Rib Cage. *J Biomech Eng* 2015; 137: 81003.

2. Bruno AG, Mokhtarzadeh H, Allaire BT, et al. Incorporation of CT-Based Measurements of Trunk Anatomy Into Subject-Specific Musculoskeletal Models of the Spine Influences Vertebral Loading Predictions. *J Orthop Res* 2017; Jan: 1–10.

3. Bruno AG, Burkhart K, Allaire B, et al. Spinal Loading Patterns from Biomechanical Modeling Explain the High Incidence of Vertebral Fractures in the Thoracolumbar Region. *J Bone Miner Res* 2017; 32(6): 1282–1290.

4. Burkhart, K. A., Bruno, A. G., Bouxsein, M. L., Bean, J. F. and Anderson, D. E. (2017), Estimating apparent maximum muscle stress of trunk extensor muscles in older adults using subject-specific musculoskeletal models. *J. Orthop. Res.*. doi: 10.1002/jor.23630