Updates and Changes to Thoracolumbar Spine Models for use in OpenSim 4.x – v2.0

Brett T. Allaire, Katelyn Burkhart, Jacob J. Banks, Dennis E. Anderson

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Summary

Previously released versions of our thoracolumbar spine model were created for use in OpenSim 3.x. While these older models can be opened in or converted for use in OpenSim 4.x, several issues have been noted. Thus we have adapted our previously released full body thoracolumbar spine models (v1.2) for use in OpenSim 4.x.

This package includes:

a. Male thoracolumbar full body model (v2.0)
b. Female thoracolumbar full body model (v2.0)
c. Updated Geometry folder

Areas of updates and changes are:

1) New rib cage geometry files to allow proper visualization
2) Change muscle models from “Thelen2003Muscle” to “Millard2012EquilibriumMuscle” to address issue with minimum allowed activation.
3) Minor changes for simplification and aesthetics.
    a. Changing path point types from “via” to “fixed”.
    b. Changed order of rotations for pelvis orientations.
    c. Reduced select joint ROMs to more reasonable ranges.
    d. Updates to color schemes.

1. Rib cage geometry file updates

The ribs and sternum in older versions (i.e., <4.x) of the model were created as three-dimensional lines in a *.vtp format. These line objects do not display in the OpenSim 4.x GUI, thus the geometry for these bodies is not visualized if loading an older model in OpenSim 4.x.

We created new three-dimensional representations of the ribs and sternum, which are included as *.obj files in the included Geometry folder. (The filenames remain the same as prior versions of the model, but the file type is different). The geometry associated with these bodies in the new OpenSim 4.x models now targets the new *.obj files.

2. Muscle model updates

Models for use in OpenSim 4.x were updated to use the “Millard2012EquilibriumMuscle” muscle model, while prior versions in OpenSim 3.x used the “Thelen2003Muscle” muscle model.

- OpenSim 4.x changed how the Thelen muscle model is handled, requiring a minimum activation of 0.01 to avoid numerical singularities that occur when activation = 0.
- The Millard muscle model prevents a numerical singularity from occurring when activation = 0; activation = 0 is allowed in OpenSim 3.x and 4.x.
- We compared models spine loading results from our models with Millard and Thelen muscle types, in both OpenSim 3.3 and OpenSim 4.0.
    - Both OpenSim 3.3 models and the OpenSim 4.0 model with Millard muscles produces essentially identical results (see Figure 1 below).
    - We see that loading is systematically increased in the OpenSim 4 model with Thelen muscles. This is because all muscles are activated to at least 0.01.

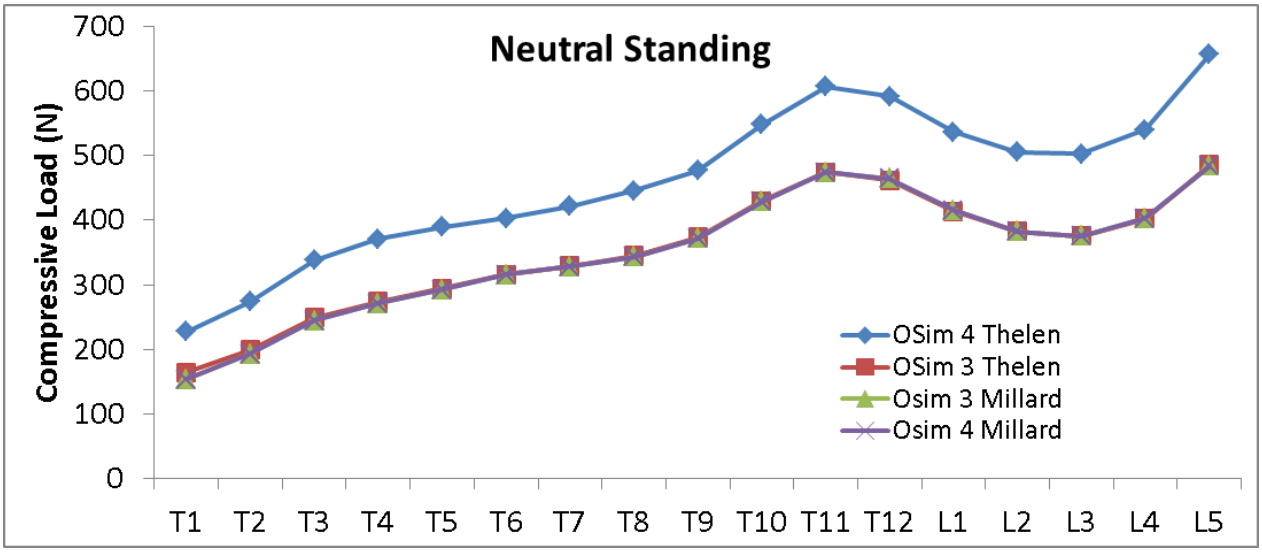

Figure 1: Compressive spine loading by vertebral level in a Neutral Standing posture, calculated by four versions of the Male thoracolumbar spine model: Thelen muscles in OpenSim 3 (previously released model), Millard muscles in OpenSim 3, Thelen muscles in OpenSim 4, Millard muscles in OpenSim 4. Note: OSim 3 Thelen, OSim 3 Millard, and OSim 4 Millard are almost indistinguishable from one another at the current scale.

3. Other Minor changes

a. Changing muscle path point types from "via" to "fixed"

We have changed all intermediate path points for trunk and spine muscles from "via" point (or "ConditionalPathPoint") to "fixed" point (or "PathPoint") types.

Many muscles in the trunk and spine used intermediate path points set to the "via" point type, which are only "on" when a specified coordinate is in a certain range. However, the "via" points for these muscles were all active for large coordinate ranges (for example L5_S1_FE from -100° to 100°) making them "always on" and functionally equivalent to "fixed" points. Thus we have revised these points to be the "fixed" path point type. This should have no effect on model outcomes, but simplifies the model specification (reducing file size) and decreases the potential for unintended outcomes due to coordinate changes.

Note: Intermediate “via” type points related to hip and knee motion were not changed in lower extremity muscles.

b. Changed order of rotations for pelvis orientations.

The pelvis serves as the first body in the model tree, connected to Ground by the ground_pelvis joint. The order of rotations for the pelvis in model version 1.2 was pelvis_tilt (AP tilt) – pelvis_list (ML tilt) – pelvis_rotation (axial rotation). However, this caused issues with appropriately specifying pelvic tilt and list when subjects were not facing “forward” (e.g. non-zero pelvis rotation) according to OpenSim’s coordinates (i.e., +X). Thus, we re-ordered the rotations to pelvis_rotation – pelvis_tilt – pelvis_list to better handle motions collected when the subject is not facing “forward” and to better accommodate differences between laboratory and OpenSim global coordinates.

c. Reduced some joint ROMs to more reasonable ranges

The range (minimum and maximum) of various coordinates of the rib cage were set to default values far outside of reasonable ranges. While ranges do not impact outcome measures from static or tracked solutions, they were often troublesome when manually manipulating the GUI. Therefore, Rib (costovertebral) and sternum rotations, which previously allowed for a range of ±90°, were changed to ±20°. Sternum translation was previously allowed in a range of ±9999 m, this was changed to ±0.05 m; moreover sternum translation coordinates are now locked by default.

d. Updates to color schemes

Bones and the “abdominal body” are now colored differently, to help further distinguish the newer versions of the model from prior versions.

Comparison of Spine Loading Outcomes vs Previous Version

To ensure model results remain similar, we evaluated spine compression for 111 simulated static postures representing a wide range of loading scenarios using the Male Thoracolumbar full body model in OpenSim 4.2 (v2.0), and in OpenSim 3.3 (v1.2). The results are reported by vertebral level in Table 1. Paired t-tests show that calculated compressive loading was lower with the OpenSim 4.2 at six vertebral levels, but the mean differences at these levels was minimal, ranging from 3 – 5 N. Root mean square differences (RMSD) ranged from 1.1% to 3.3%, and intraclass correlation coefficients (ICC) were >0.995 at all levels. Overall, these results show that predictions of spine loading using the model in OpenSim 4.x have excellent validity and minimal differences compared to the previously released and validated version in OpenSim 3.

Table 1: Comparison of spine compressive loading estimates for 111 simulated static postures from thoracolumbar spine models in OpenSim 3.3 and 4.2.

	OpenSim 3.3 Loading (N)		OpenSim 4.2 Loading (N)				
Level	Mean	SD	Mean	SD	p-value	RMSD (%)	ICC
T1	285	103	282	102	**0.004**	3.3%	0.996
T2	344	124	343	124	0.675	2.5%	0.998
T3	400	147	402	148	0.104	2.0%	0.998
T4	430	162	430	162	0.803	1.8%	0.999
T5	475	179	471	178	**<0.001**	2.0%	0.998
T6	523	195	518	193	**<0.001**	2.2%	0.998
T7	640	254	636	251	**<0.001**	2.0%	0.998
T8	787	329	782	326	**0.001**	1.8%	0.999
T9	845	353	841	353	**0.004**	1.8%	0.999
T10	942	406	940	409	0.307	1.8%	0.999
T11	1043	460	1043	465	0.921	1.6%	0.999
T12	1030	458	1029	464	0.784	1.4%	0.999
L1	975	440	974	445	0.472	1.3%	0.999
L2	920	412	920	414	0.608	1.1%	0.999
L3	876	380	876	381	0.611	1.1%	0.999
L4	892	371	893	371	0.353	1.1%	0.999
L5	1013	402	1014	402	0.359	1.2%	0.999

Contact

For any additional details or inquiries, please reach out to any of the members of our lab:

- Brett T. Allaire: ballaire@bidmc.harvard.edu
- Katelyn Burkhart: kburkhar@bidmc.harvard.edu
- Jacob J. Banks: jbanks3@bidmc.harvard.edu
- Dennis E. Anderson: danders7@bidmc.harvard.edu