6/8/2020 **Overview of updates to the model and modeling environment**

In our prior publication (Saul KR, Hu X, Goehler CM, Daly M, Vidt ME, Velisar A, Murray WM. Benchmarking of dynamic simulation predictions in two software platforms using an upper limb musculoskeletal model. Computer Methods in Biomechanics and Biomedical Engineering. 2015; 18:1445-58)1, we described simulations performed in the OpenSim modeling platform and compared these results to simulations run using a comparable model in the SIMM-Dynamics Pipeline-SD/Fast environment. In that study, we illustrated that differences in algorithmic implementation in these two software platforms widely used by the biomechanics community for the simulation of movement can affect simulation predictions. Specifically, we demonstrated the most substantial divergence arose from different implementations of muscle paths and force generation in the two software platforms. At the time of publication, the two software platforms (specifically, OpenSim 2.4 and SIMM version 4.2.1, Dynamics Pipeline, version 3.3, SD/Fast version B.2.8) used different algorithms to calculate muscle moment arm for muscle paths that included moving muscle points2. In addition, OpenSim did not enable moving points defined to exist only within a specified range of motion; the biceps actuators in the SIMM model each had a single point of this type. These differences between platforms led to the most substantial differences in simulation results between platforms.

**3.2 Compatibility Update**

Since publication of Saul et al.1, substantial changes were made to the OpenSim environment in release 3.2 and later releases that pertain to the calculation of moment arm and the handling of moving points. Thus, we have revisited both the model and the simulation results for compatibility with the most recent implementation of OpenSim and comparisons between platforms. Specifically, OpenSim now uses the same algorithm as SIMM to calculate muscle moment arm when paths include moving muscle points. Based on this change, muscle paths and tendon slack lengths that were altered to accommodate the moment arm calculation in OpenSim v2.4 were restored to match those implemented for the same muscles in SIMM. (See summary tables) Thus, these aspects of the model are now identical between platforms.

As an additional new difference between platforms, OpenSim no longer permits moving muscle points for which the motion depends on two separate coordinates. The biceps (short and long head) included moving muscle points of this type. In addition, the scaling tool in OpenSim does not natively scale any joints that have translations; one joint of this type was used to accommodate the complex movement of the middle deltoid and allow dependence on multiple coordinates. To address these issues and allow this model to be used in later versions of OpenSim, we have replaced the moving points in question with new points that depend only on a single coordinate (forearm rotation for biceps and shoulder rotation for deltoid). Finally, the single biceps moving point that was defined to exist only within a specified range of motion was removed. These changes result in implementation that remains different between SIMM and OpenSim.

**Recent updates**

Since the 3.2 Compatibility update, several additional changes were made to the upper extremity model. First, we have update muscle model from the deprecated Schutte 1993 Model3 to the Millard 2012 Equilibrium Muscle Model4. Force-length and tendon curves in the Millard model were updated to reflected the original force-length, force-velocity, and tendon curves from the Schutte model as described in Binder-Markey and Murray5. Secondly, the range of motion at the shoulder was expanded to permit a full range of motion observed during experimental data collection of functional tasks such as axial wash as described in Vidt et al.6. Specifically, elevation plane range of motion was expanded to allow -95⁰ to 130⁰ of rotation and humeral axial rotation range of motion was expanded to permit -90⁰ to 120⁰ of rotation. Muscle paths and surfaces were updated to ensure proper interaction of muscle actuators with their respective associated wrapping surfaces in this expanded range of motion. Muscle paths and behavior within the previously described joint limits were unaltered. Lastly, ligament models representing the coracohumeral ligament and the superior, middle, inferior portions of the glenohumeral ligament were included as described in McFarland et al.7. Attachment points were approximated from mean insertion and origin data obtained in an anatomical study8. Mechanical properties of the ligament models were defined from previous tensile strength studies9, 10.

**Summary of updates to model, parameter tables, and benchmarking simulations.**

The latest version of the model is located Model folder. Here we include models for both 3.3 and 4.1 since 4.1 models are not backwards compatible. Note that when importing the 3.3 model into the 4.1 environment the coordinatelimitforce for wrist flexion and deviation needs to be updated from degrees to radians. This conversion has already been applied to the 4.1 model. For both 3.3 and 4.1, there are two models in the respective folders: one with torso rotation and translation and another where the torso is fixed. Below are detailed tables with a summary of force-generating parameters (Table 1), changes to muscle paths (Table 2), and changes to wrapping surfaces (Table 3). For the benchmarking simulations, model changes pertain to tutorial modules 2-7 which use a partial model in gravity-driven forward simulations and the full model in gravity-driven forward simulations, EMG-driven simulations, scaling and inverse kinematics processing, CMC analysis, and CMC-driven forward dynamic simulations. Models required for the benchmarking simulations are located within the benchmarking folder. The required model for each model is identified in the model name. For example MoBL\_ARMS\_module5\_scaleIK is used in module 5. These models are derived from the model in the main model folder, but for certain simulations degrees of freedom or muscles have been purposely removed from the main model.

**Simulation benchmarking.**

New simulations using the revised model have been performed to elucidate the effect of the platform and model upgrade, and to provide new benchmarking data for the community. In brief, switching to the Millard muscle model resulted in less oscillations during passive simulations, but overall behavior of the model was similar to the original simulations. This is likely due to the small amount of damping included in the Millard muscle model. In some cases, results became more similar to the results in SIMM and in some cases results became less similar. Passive wrist simulations had the largest difference from original simulations and now settles at 18° flexion instead of 34° flexion. EMG driven simulations resulted in similar motion to the original simulations, but with less steep peaks. Forward dynamic results from CMC predicted controls resulted in similar results to the original OpenSim results. There were no differences in results between OpenSim 3.3 and OpenSim 4.1 for modules 1-5 and module 7. Module 6 (CMC) produced nearly identical results between OpenSim versions. Overall, the original Millard muscle model produced similar motions to the model with the Millard-Schutte matched force-length and tendon curves. However, in general, simulations with the original Millard muscle model were less similar to the original results in the published paper. In summary, the sensitivity of optimization-driven simulations to the specific platform and model persist, as expected. These results and models have been released for public use. These platform revisions highlight the utility of a benchmarking dataset to allow for model development and interpretation in the context of new software and software upgrades.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Muscle** | **Abbrev** | **Optimal Fiber Length (cm)** | **Peak Force (N)** | **Tendon Slack Length (cm)** | **Pennation Angle (o)** |
| ***Shoulder*** |  |  |  |  |  |
| Deltoid |  |  |  |  |  |
| Anterior | DELT1 | 9.8 | 1218.9 | 9.3 | 22 |
| Middle | DELT2 | 10.8 | 1103.5 | 11 | 15 |
| Posterior | DELT3 | 13.7 | 201.6 | 3.8 | 18 |
| Supraspinatus | SUPRA | 6.8 | 499.2 | 4 | 7 |
| Infraspinatus | INFRA | 7.6 | 1075.8 | 3.1 | 19 |
| Subscapularis | SUBSC | 8.7 | 1306.9 | 3.3 | 20 |
| Teres minor | TMIN | 7.4 | 269.5 | 7.1 | 24 |
| Teres major | TMAJ | 16.2 | 144 | 2 | 16 |
| Pectoralis major |  |  |  |  |  |
| Clavicular | PECM1 | 14.4 | 444.3 | 0.3 | 17 |
| Sternal | PECM2 | 13.8 | 658.3 | 8.9 | 26 |
| Ribs | PECM3 | 13.8 | 498.1 | 13.2 | 25 |
| Latissimus dorsi |  |  |  |  |  |
| Thoracic | LAT1 | 25.4 | 290.5 | 12 | 25 |
| Lumbar | LAT2 | 23.2 | 317.5 | 17.7 | 19 |
| Iliac | LAT3 | 27.9 | 189 | 14 | 21 |
| Coracobrachialis | CORB | 9.3 | 208.2 | 9.7 | 27 |
| ***Elbow*** |  |  |  |  |  |
| Triceps |  |  |  |  |  |
| Long | TRIlong | 13.4 | 771.8 | 14.3 | 12 |
| Lateral | TRIlat | 11.4 | 717.5 | 9.8 | 9 |
| Medial | TRImed | 11.4 | 717.5 | 9.1 | 9 |
| Anconeus | ANC | 2.7 | 283.2 | 1.8 | 0 |
| Supinator | SUPRA | 3.3 | 379.6 | 2.8 | 0 |
| Biceps |  |  |  |  |  |
| Long | BIClong | 11.6 | 525.1 | 27.2 | 0 |
| Short | BICshort | 13.2 | 316.8 | 19.2 | 0 |
| Brachialis | BRA | 8.6 | 1177.4 | 5.4 | 0 |
| Brachioradialis | BRD | 17.3 | 276 | 13.3 | 0 |
| ***Major wrist or forearm*** |  |  |  |  |  |
| Extensor carpi radialis longus | ECRL | 8.1 | 337.3 | 24.4 | 0 |
| Extensor carpi radialis brevis | ECRB | 5.9 | 252.5 | 22.2 | 9 |
| Extensor carpi ulnaris | ECU | 6.2 | 192.9 | 22.9 | 4 |
| Flexor Carpi radialis | FCR | 6.3 | 407.9 | 24.4 | 3 |
| Flexor capri ulnaris | FCU | 5.1 | 479.8 | 26.5 | 12 |
| Palmaris longus | PL | 6.4 | 101 | 26.9 | 4 |
| Pronator teres | PT | 4.9 | 557.2 | 9.8 | 10 |
| Pronator quadratus | PQ | 2.8 | 284.7 | 0.5 | 10 |
| ***Wrist/hand muscles*** |  |  |  |  |  |
| Flexor digitorum superficialis |  |  |  |  |  |
| Digit 5 | FDSL | 5.2 | 75.3 | 33.9 | 5 |
| Digit 4 | FDSR | 7.4 | 171.2 | 32.8 | 4 |
| Digit 3 | FDSM | 7.5 | 258.8 | 29.5 | 7 |
| Digit 2 | FDSI | 8.4 | 162.5 | 27.5 | 6 |
| Flexor digitorum produndus |  |  |  |  |  |
| Digit 5 | FDPL | 7.5 | 236.8 | 28.2 | 8 |
| Digit 4 | FDPR | 8 | 172.9 | 29.2 | 7 |
| Digit 3 | FDPM | 8.4 | 212.4 | 30.3 | 6 |
| Digit 2 | FDPI | 7.5 | 197.3 | 30.2 | 7 |
| Extensor digitorum communis |  |  |  |  |  |
| Digit 5 | EDCL | 6.5 | 39.4 | 33.5 | 2 |
| Digit 4 | EDCR | 6.3 | 109.2 | 36.5 | 3 |
| Digit 3 | EDCM | 7.2 | 94.4 | 36.5 | 3 |
| Digit 2 | EDCI | 7 | 48.8 | 36.5 | 3 |
| Extensor digiti minimi | EDM | 6.8 | 72.4 | 33.5 | 3 |
| Extensor indicis propius | EIP | 5.9 | 47.3 | 21 | 6 |
| Extensor pollicis longus | EPL | 5.4 | 88.3 | 23.1 | 6 |
| Extensor pollicis brevis | EPB | 6.8 | 46 | 11.6 | 7 |
| Flexor pollicis longus | FPL | 5.5 | 201 | 19.7 | 7 |
| Abductor pollicis longus | APL | 7.1 | 116.7 | 13 | 8 |

**Table 1: Force-generating parameter table.**

**Table 2: Summary of changes to muscle path points**. Notes: Delt2-P2 was originally attached to Delt2pt2a and depended on shoulder rotation, and is now attached to the humerus and depends on shoulder rotation. Both Biclong-P9 and Bicshort-P6 Y spline originally depended on elbow flexion and now depend on pronation supination. Conditional path points Biclong-P10 and Bicshort-P7 were removed.

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Muscle | Path Point | Type | Original Coordinate | | | | New Coordinate | | | | Update |
| Delt1 | Delt1-P3 | Location | 0.04347 | -0.0320 | 0.00139 | | 0.04347 | -0.0320 | 0.00499 | | 3.2 |
| Delt2 | Delt2-P2 | X Spline | 0.03804 | | -0.00604 | | 0.03804 | | 0 | | 3.2 |
| Y Spline | -0.0419 | -0.0391 | -0.03012 | | -0.0619 | | -0.06012 | |
| Z Spline | 0.00208 | 0.020303 | 0.04032 | | 0.00208 | 0.0203027 | 0.02532 | |
| TMAJ | Conditional: shoulder\_rot | Location | - | - | - | | 0.009 | -0.054 | -0.009 | | ROM |
| Conditional: elv\_angle | Location | - | - | - | | 0.009 | -0.054 | -0.009 | |
| PECM1 | PECM1-P3 | X Spline | 0.00458 | | -0.02372 | | 0.00958 | | -0.00972 | | 3.2 |
| Y Spline | -0.01309 | | 0.04151 | | -0.01509 | | 0.03151 | |
| PECM2 | PECM2-P3 | Y Spline | -0.03965 | | 0.00055 | | -0.04165 | | 0.00155 | | 3.2 |
| Z Spline | 0.1259 | | 0.1102 | | 0.1269 | | 0.1042 | |
| PECM2-P4 | Location | 0.03091 | -0.03522 | 0.09705 | | 0.03091 | -0.03922 | 0.09705 | |
| PECM3 | PECM3-P2 | X Spline | 0.01243 | 0.01491 | 0.01833 | | 0.01243 | 0.014912 | 0.01833 | | 3.2 |
| Y Spline | -0.04757 | | -0.0361 | | -0.05157 | | -0.040096 | |
| Z Spline | -0.0181 | -0.0081 | 0 | 0 | -0.0181 | -0.0081 | 0 | 0 |
| PECM3-P3 | Y Spline | -0.0728 | -0.0558 | -0.0289 | | -0.0708 | -0.0598 | -0.0269 | |
| Z Spline | 0.1151 | | 0.1101 | | 0.1151 | | 0.1151 | |
| LAT1 | LAT1-P2 | X Spline | -0.07247 | | -0.07957 | | -0.07947 | | -0.08157 | | 3.2 |
| Y Spline | -0.08481 | | -0.04961 | | -0.08581 | | -0.05061 | |
| LAT1-P3 | X Spline | -0.11015 | | -0.10435 | | -0.11215 | | -0.10635 | |
| Y Spline | -0.09079 | | -0.00699 | | -0.09779 | | -0.04699 | |
| Conditional: shoulder\_rot | Location | - | - | - | | 0.01 | -0.035 | -0.00889323 | | ROM |
| Conditional: elv\_angle | Location | - | - | - | | 0.01 | -0.035 | -0.009 | |
| LAT2 | LAT2-P2 | X Spline | -0.0764 | | -0.0904 | | -0.0764 | | -0.0905 | | 3.2 |
| Y Spline | -0.0922 | | -0.0717 | | -0.1022 | | -0.0717 | |
| Conditional: shoulder\_rot | Location | - | - | - | | 0.008 | -0.043 | -0.01 | | ROM |
| Conditional: elv\_angle | Location | - | - | - | | 0.008 | -0.04339 | -0.0100971 | |
| LAT3 | LAT3-P2 | Y Spline | -0.13303 | | -0.09093 | | -0.13303 | | -0.09893 | | 3.2 |
| Z Spline | -0.0173 | | -0.0466 | | -0.0213 | | -0.0386 | |
| LAT3-P3 | Y Spline | -0.16953 | | -0.09313 | | -0.17553 | | -0.10113 | |
| Z Spline | -0.04406 | | -0.15016 | | -0.04406 | | -0.13416 | |
| Conditional: shoulder\_rot | Location | - | - | - | | 0.01 | -0.041 | -0.009 | | ROM |
| Conditional: elv\_angle | Location | - | - | - | | 0.01 | -0.041 | -0.009 | |
| BIClong | BIClong-p2 | Location | -0.0228 | -0.01309 | -0.0067 | | -0.0209 | -0.0131 | -0.00461 | | 3.2 |
| BIClong-p9 | X Spline | -0.0055 | | 0.00796 | | -0.0055 | | 0.01096 | |
| Y Spline | -0.0232 | | -0.04016 | | -0.0282 | -0.035 | -0.0392 | |
| Z Spline | 0 | -0.00598 | -0.00033 | | -0.01 | -0.01358 | -0.01083 | |
| BICshort | BICshort-P6 | X Spline | -0.0055 | | 0.00796 | | -0.0055 | | 0.01096 | | 3.2 |
| Y Spline | -0.0232 | | -0.04016 | | -0.0282 | -0.035 | -0.0392 | |
| Z Spline | 0 | -0.00598 | -0.00033 | | -0.01 | -0.01358 | -0.01083 | |
| FPL | FPL-P5 | X Spline | 0 | -0.00598 | -0.00033 | | 0.01869 | 0.01869 | 0.01549 | | 3.2 |
| Y Spline | 0.01869 | 0.01869 | 0.01229 | | 0.00882 | 0.00882 | -0.00078 | |
| Z Spline | 0.00882 | 0.00882 | -0.01038 | | -0.0155 | -0.0155 | -0.02087 | |
| APL | APL-P6 | X Spline | -0.0155 | -0.01547 | -0.0263 | | 0.03385 | 0.03385 | 0.03135 | | 3.2 |
| Y Spline | 0.03385 | 0.0336 | 0.0276 | | 0.00634 | 0.00634 | 0.00534 | |
| Z Spline | 0.00634 | 0.00624 | 0.00384 | | -0.0075 | -0.0075 | -0.01245 | |

**Table 3: Summary of changes to wrap surfaces**.

|  |  |  |
| --- | --- | --- |
| Wrap surface | Paths Affected | Change |
| infsp\_new | INFSP | infsp\_new replaces INFSP\_and\_TMIN\_hum\_head for INFSP |
| LIGhh\_s | s\_glenohum, coracohum | wrap surface for s\_glenohum and coracohum ligaments added |
| LIGhh\_mi | m\_glenohum,i\_glenohum | wrap surface for m\_glenohum and i\_glenohum ligaments added |
| TMINhum | TMIN | body rotation changed from 1.75353 0.0692896 2.74628 to 1.47353 0.0229 3.21463 |
| translation changed from -0.0014 -0.0455 0 to 0.003 -0.0255 0.0013 |
| cylinder radius changed from 0.007 to 0.022 |
| cylinder length changed from 0.07 to 0.113 |
| LAT\_TMAJ2hh | TMAJ,LAT1, LAT2, LAT3 | quadrant changed from -z to all |
| BIClong | BIClong | translation changed from 0.0033 0.0073 0.0003 to 0.0033 0.005 0.0003 |
| TRIlongglen | TRIlong | wrap changed from -1 -1 to 1 2 |

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