The effect of simplifying the scaling method of an upper limb musculoskeletal model on the joint angles

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Introduction

Scaling cadaver-based musculoskeletal models of the upper limbs is an important step prior to performing musculoskeletal analysis. These models are commonly scaled using three-dimensional (3D) optical marker data; however, this approach can be time-consuming and difficult for individuals with limited trunk stability (i.e. individuals with cervical level of spinal cord injury).

Research Question

What are the effects of simplified scaling methods on joint angles for an upper limb musculoskeletal model?

Methods

Two able-bodied individuals consented to participate in upper limb repeated trials of shoulder flexion and abduction, external rotation of the arm, and hand-to-head movements. Retroreflective marker clusters were placed on the sternum, acromion, humerus, forearm, and hand [1]. Markers were tracked at 100 Hz using a Vicon motion capture system. The marker coordinates were used to scale an upper limb model in OpenSim 4.1 [2], creating a representative model for each participant. In the ideal model, the bone segments were scaled with marker pairs parallel to their coordinate systems. For example, to scale the scapula, virtual markers were created from the projection of the bony landmark markers, and these markers were used to scale the scapula accordingly along each axis.

Six new models were created following different simplified scaling configurations, based on marker pairs of bony landmarks accessible for manual measurement on impaired individuals (Table 1). Joint angles were calculated via inverse kinematic analyses. Root mean square (RMS) errors were calculated to show the differences between the outputs of the six new models relative to the ideal model.

Results

For both participants, method one (non-uniformly scaled scapula and thorax) showed small RMS errors compared to the other methods. In one participant, the scapula angles' median (range) RMS errors were 0.52° (0.32°-0.68°), 0.25° (0.09°-0.37°), 0.78° (0.40°-0.95°), 0.29° (0.18°-0.45°) for protraction, elevation, upward and internal rotations, respectively. The RMS errors for scapular angles from method two were slightly higher compared to method one. In method three, the RMS errors for the scapular angles were similar to those found in method one. The RMS errors were noticeably higher in methods five and six (scapula and thorax uniformly scaled). A similar pattern was observed for the clavicular and glenohumeral joint angles.

Discussion

Applying different scaling methods to the upper limb musculoskeletal model resulted in small but noticeably different joint angles. The angles from method one best matched the ideal model producing small RMS errors. This indicates that measurements that could easily be estimated with a tape and caliper can be used in scaling an upper limb musculoskeletal model and approach the accuracy of scaling performed with 3D marker coordinates. Future research currently underway focuses on the effect of different scaling configuration on net joint torques and muscle forces.

References

[1] E. Jaspers, H. Feys, H. Bruyninckx, K. Klingels, G. Molenaers, K. Desloovere, The Arm Profile Score: A new summary index to assess upper limb movement pathology, Gait Posture. 34 (2011) 227–233. https://doi.org/10.1016/j.gaitpost.2011.05.003.

[2] A. Seth, M. Dong, R. Matias, S. Delp, Muscle Contributions to Upper-Extremity Movement and Work From a Musculoskeletal Model of the Human Shoulder, Front. Neurorobotics. 13 (2019). https://doi.org/10.3389/fnbot.2019.00090.

Table 1: Scaling configurations showing marker pairs used during each method. In the ideal method thorax and scapula were scaled with virtual and bony landmark marker pairs parallel to their coordinate systems. Method 1, both thorax and scapula non-uniformly scaled. Method 2, thorax is uniformly scaled and scapula non-uniformly scaled. Method 3 and 4, thorax is non-uniformly scaled, and scapula is uniformly scaled. Method 5 and 6, thorax and scapula were uniformly scaled.

Abbreviations: ij, Insicura Jungularis; c7, C7 Spinous Process; px, Processus Xiphoideus; ac, Articulatio acromioclavicularis; ai, Angulus Inferior; aa, Angulus Acromialis; ts, Trigonum Scapulae; EpL, Lateral epicondyle; EpM, Medial epicondyle; centelbow, center of elbow; gh, glenohumeral joint; us, Ulnar Styloid; rs, Radial Styloid.

<table>
<tr><th>Segments</th><th></th><th>Ideal Method</th><th>Method 1</th><th>Method 2</th><th>Method 3</th><th>Method 4</th><th>Method 5</th><th>Method 6</th></tr>
<tr><td rowspan="3">Thorax</td><td>x</td><td>ij_proj_c7 & ij</td><td>c7 & ij</td><td rowspan="3">px & ij</td><td>c7 & ij</td><td>c7 & ij</td><td rowspan="3">px & ij</td><td rowspan="3">px & ij</td></tr>
<tr><td>y</td><td>ij_proj_px & ij</td><td>px & ij</td><td>px & ij</td><td>px & ij</td></tr>
<tr><td>z</td><td>ij_proj_ac & ij</td><td>ac & ij</td><td>ac & ij</td><td>ac & ij</td></tr>
<tr><td rowspan="3">Scapula</td><td>x</td><td>ai_proj_aa_x & ai</td><td colspan="2">pc & aa</td><td rowspan="3">pc & aa</td><td rowspan="3">ts & aa</td><td rowspan="3">pc & aa</td><td rowspan="3">ts & aa</td></tr>
<tr><td>y</td><td>ai_proj_ts & ai</td><td colspan="2">ts & ai</td></tr>
<tr><td>z</td><td>ai_proj_aa_z & ai</td><td colspan="2">ts & aa</td></tr>
<tr><td>Clavicle</td><td>y</td><td colspan="7">ij & ac</td></tr>
<tr><td rowspan="3">Humerus</td><td>x</td><td colspan="7">EpL & EpM</td></tr>
<tr><td>y</td><td colspan="7">centelbow & gh</td></tr>
<tr><td>z</td><td colspan="7">EpL & EpM</td></tr>
<tr><td rowspan="3">Ulna & Radius</td><td>x</td><td colspan="7">us & rs</td></tr>
<tr><td>y</td><td colspan="7">centelbow & gh</td></tr>
<tr><td>z</td><td colspan="7">us & rs</td></tr>
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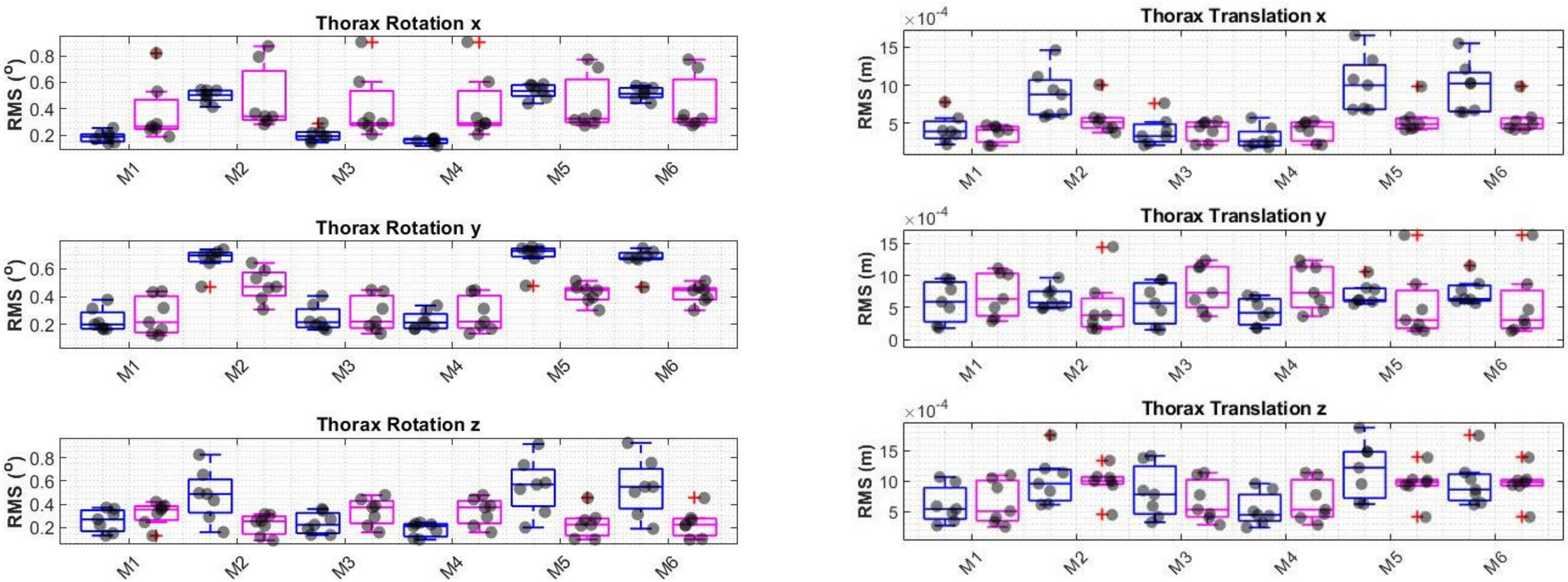
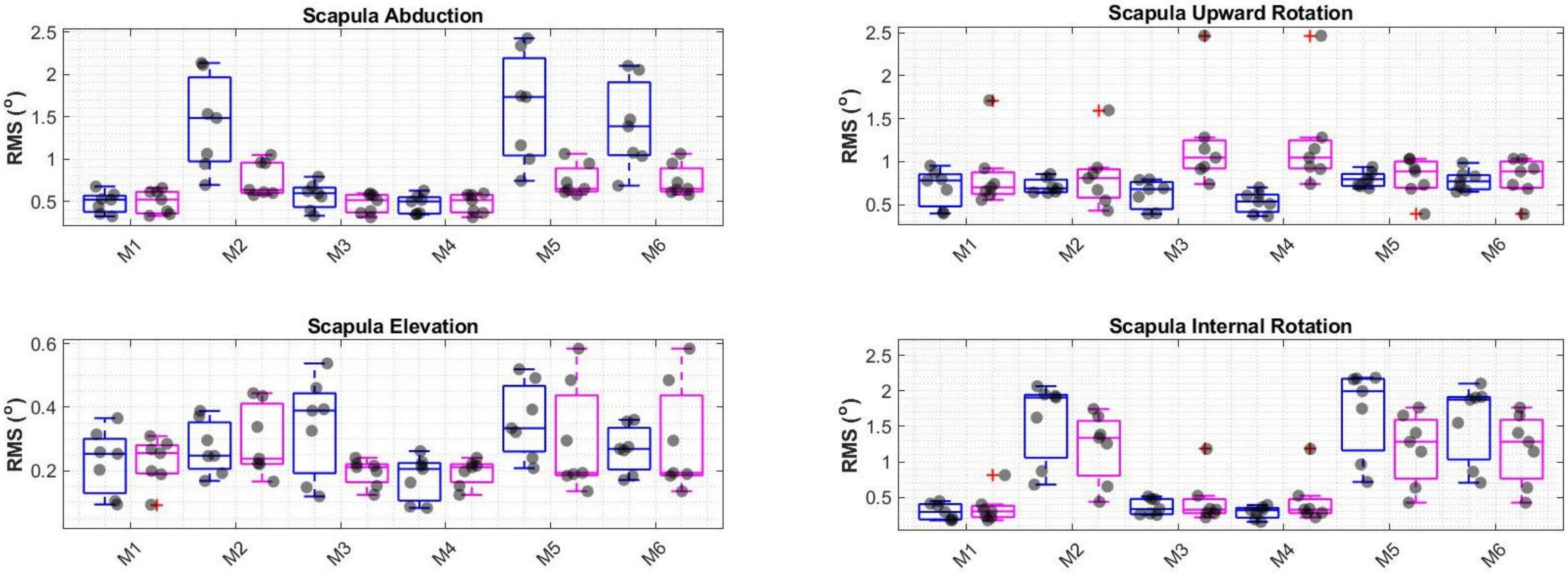
Results (Supplementary Materials)

The following box-and-whisker figures show RMS errors between the ideal method of scaling a shoulder musculoskeletal model and simplified methods. All methods of scaling the model including the ideal method is described in the table below. Blue boxes are subject 2 and magenta boxes are subject 3.

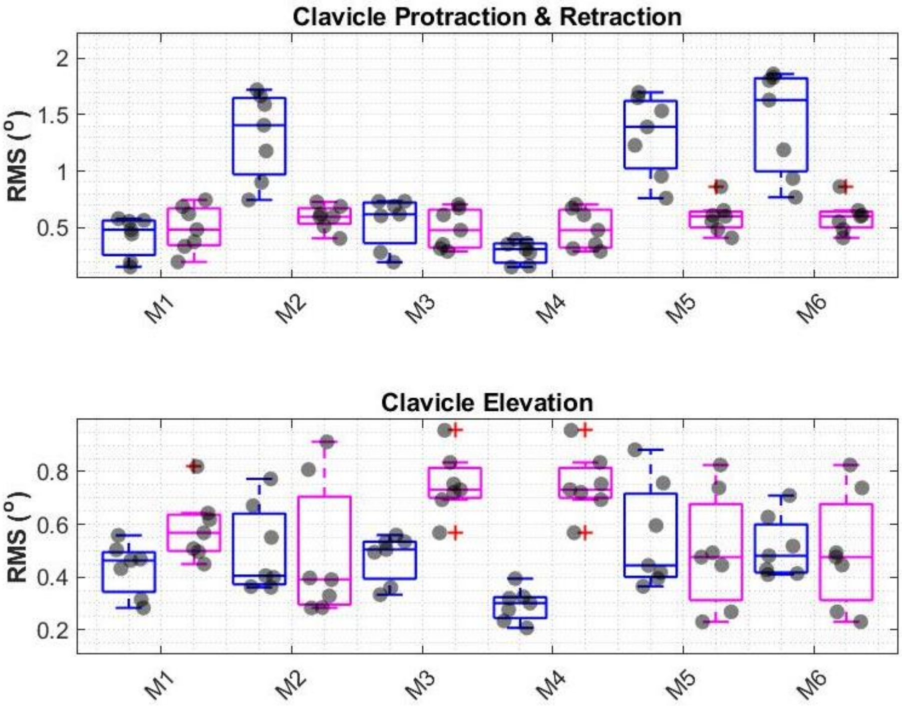
1. Thorax movement (rotation and translation in x, y and z directions)



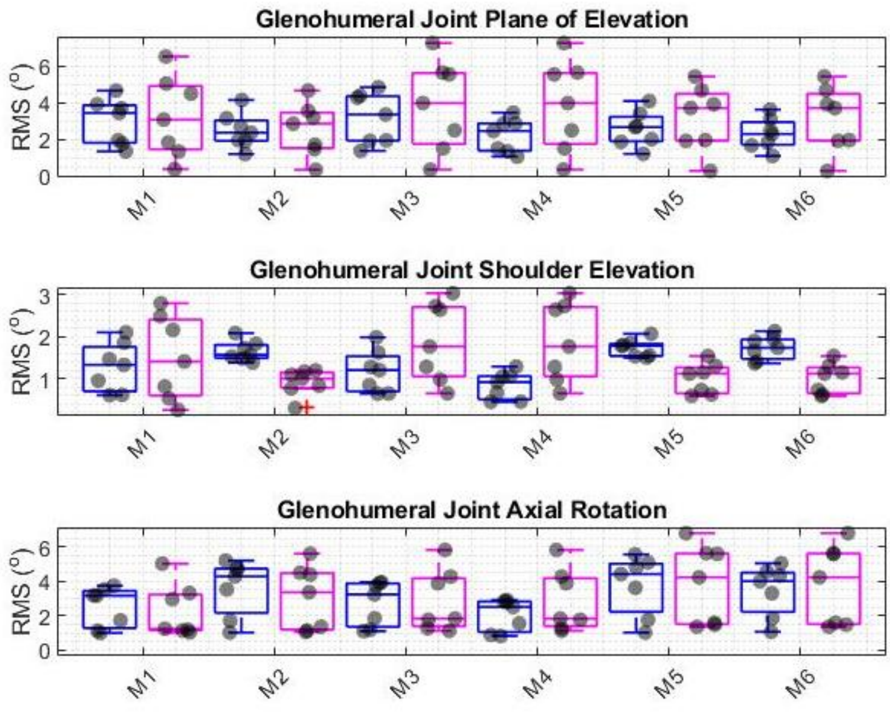
2. Scapula movement (abduction, elevation, upward and internal rotations)



3. Clavicular movement (protraction and elevation)



4. Glenohumeral joint movement (plane of and shoulder elevations, and axial rotation)



5. Forearm movement (pronation and supination, and elbow flexion)