Modeling independent scapular motion for more robust upper limb modeling studies

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INTRODUCTION: Computational models are powerful tools that can be used to investigate the biomechanical underpinnings of joint motion in different clinical populations that are not feasible experimentally1. As computational model use increases in shoulder mechanics research, it is necessary to include features that make these models more biofidelic2, including representation of arthrokineimatics that can vary across populations and injury. Specifically, altered scapular kinematics have been implicated in scapulothoracic injuries1. Current models, such as the upper limb model in OpenSim3 (MoBL-ARMS4) define scapular motion by a series of regression equations5. However, scapular kinematics are known to change after injury and influence upper extremity function1. Recently, researchers have developed an upper extremity model (Scapulothoracic Joint model6) that includes independent scapular motion; however it does not include muscle representations which are needed for studying dynamic movements. Our objective was to enhance the biofidelity of the MoBL-ARMS model by incorporating independent scapular degrees of freedom to permit more robust studies of shoulder and upper limb function.

METHODS: The MoBL-ARMS upper extremity model in OpenSim (v3.3) was used as the baseline for development of the new MUSL model. The Scapulothoracic Joint model, which includes a custom plug-in describing the scapulothoracic joint and independent scapular motion, was used as a foundation for incorporating scapulothoracic articulations into the newly developed MUSL model. Scapular motion is defined by 4 degrees of freedom, including: abduction, elevation, upward rotation, and winging (Fig. 1). The plug-in describing these degrees of freedom and the axes about which scapular rotations occur, and the constraints defining the scapulothoracic joint were identified and extracted. They were then implemented to replace the regression equations previously defining scapular kinematics as a function of thoracohumeral elevation. Contact geometry was added to the scapula and thorax to prevent the segments from passing through each other for any posture or dynamic movement. To validate the addition of independent scapular degrees of freedom, published bone pin marker data6 of humeral abduction derived from human subjects performing humeral elevation tasks in the frontal plane were evaluated. Notably, this data set was the same that was used by researchers to validate the Scapulothoracic Joint model1. The bone pin data were used as inputs to the scale tool, followed by the inverse kinematics tool in OpenSim. The same procedures were performed with both the Scapulothoracic Joint model and the MUSL model developed here. Results from inverse kinematics were smoothed with a zero-phase 4th order Butterworth filter with a 6Hz cutoff frequency using a custom MATLAB script (The MathWorks, Inc.). The maximum difference and RMSE of the 4 scapular degrees of freedom were separately computed and compared between the MUSL model and the Scapulothoracic Joint model. Gravity-driven simulations of thoracohumeral abduction were used to verify contact geometry implementation by determining the engagement angle, which is the angle for each scapular degree of freedom where a contact geometry is engaged.

RESULTS: Simulations were successfully run with each of the models. Maximum differences were computed, with positive values indicating engagement angles (dashed) for each scapular degree of freedom. Joint angles for scapular degrees of freedom during a thoracohumeral abduction task for the MUSL model (solid) and the Scapulothoracic Joint model (dashed), with small maximum difference (≤2.42°) and RMSE (≤2.42°) values for all degrees of freedom.

DISCUSSION: The MUSL model developed here matches the kinematics calculated by the Scapulothoracic Joint model with a maximum angle difference of ≤4.34° for each degree of freedom and RMSE values of ≤2.42° for each scapular degree of freedom, providing initial model validation. Inclusion of scapula and thorax contact geometries ensure scapular joint angles remain within physiological ranges during dynamic movements. Ongoing work seeks to include muscle actuators for scapular stabilizing muscles (e.g. trapezius, serratus anterior) and validate against other reported scapular motion data6.

SIGNIFICANCE/CLINICAL RELEVANCE: Development of a more biofidelic computational model is necessary for detailed study of shoulder and upper limb motion across populations and in the context of injury. The inclusion of independent scapular motion in the model will facilitate future clinical translation of modeling tools for more accurate design of treatment and rehabilitation strategies for patients with upper limb injuries.


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IMAGES AND TABLES: