Modeling independent scapular motion for more robust upper limb modeling studies

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Disclosures: Joshua Pataky (N), Meghan E. Vidt (N).

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 experimentally[1]. As computational model use increases in shoulder mechanics research, it is necessary to include features that make these models more biofidelic[2], including representation of arthrokinematics that can vary across populations and injury. Specifically, altered scapular kinematics have been implicated in scapulothoracic injuries[3]. Current models, such as the upper limb model in OpenSim[4] (MoBL-ARMS[5]) define scapular motion by a series of regression equations[6]. However, scapular kinematics are known to change after injury and influence upper extremity function[3]. Recently, researchers have developed an upper extremity model (Scapulothoracic Joint model[7]) 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[6] 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 data[8] 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 model[7]. 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 adduction were used to verify contact geometry implementation by determining the engagement angle, which is the angle for each scapular degree of freedom where a force response occurs.

RESULTS SECTION: Simulations were successfully run with each of the models. Maximum differences were computed, with positive values indicating that the MUSL model had a greater joint angle than the Scapulothoracic Joint model. Scapular degrees of freedom of the MUSL model compared to the Scapulothoracic Joint model were: 4.33° in scapular abduction, -0.33° in scapular elevation, -2.51° in scapular upward rotation, and 1.21° in scapular winging (**Fig. 2**). RMSEs were: 2.42° in scapular abduction, 0.17° in scapular elevation, 1.38° in scapular upward rotation, and 0.73° in scapular winging. When the force response of the implemented contact geometry occurred at 33.25° in scapular abduction, -8.92° in scapular elevation, -16.76° in scapular upward rotation, and -4.32° in scapular winging, scapular joint angles rapidly returned to acceptable ranges (**Fig. 3**).

DISCUSSION: The MUSL model developed here matches the kinematics calculated by the Scapulothoracic Joint model with a maximum angle difference of ≤4.33° 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 data[9].

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.

REFERENCES: [1] Magermans et al. (2004), *Clin Biomech* 19(4):350-357; [2] Morrow et al. (2022), *J Electromyogr Kinesiol* 62:102409; [3] Huang et al. (2015), *J Shoulder Elb Surg* 24(8):1227-1234; [4] Delp et al. (2007), *IEEE* 54(11):1940-1950; [5] Saul et al. (2015), *Comput Methods Biomech Biomed Eng* 18(13):1445-1458; [6] de Groot & Brand (2001), *Clin Biomech* 16(9):735-743; [7] Seth et al. 2016, *PLoS ONE* 11(1):e0141028; [8] Ludewig et al. (2009), *J Bone Joint Surg AM* 91:378-389; [8] Borstad & Ludewig (2002), *Clin Biomech* 17(9-10):650-659; [9] Karduna et al. (2001), *J Biomech Eng* 123(2):184-190.

ACKNOWLEDGEMENTS: NSF-CBET #2103440 (Vidt)

IMAGES AND TABLES:

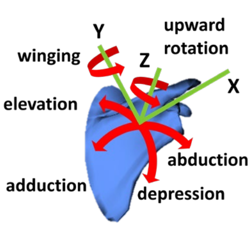

Figure 1: Four degrees of freedom defining independent scapular motion, including: abduction, elevation, upward rotation, and winging.

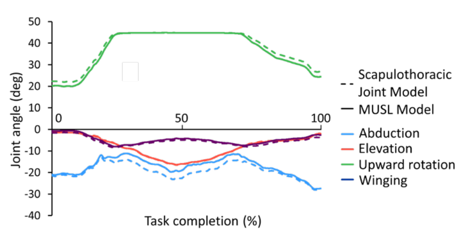

Figure 2: Joint angles for scapular degrees of freedom during a thoracohumeral abduction task for the MUSL model (solid) and the Scapulothoracic Joint model (dashed), with small maximum difference (≤4.33°) and RMSE (≤2.42°) values for all degrees of freedom.

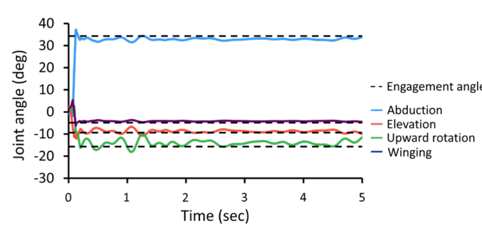

Figure 3: Joint angles for scapular degrees of freedom during a gravity-driven simulation (solid) and the engagement angle between contact geometries (dashed).