# Effects of Constrained and Unconstrained Joint Parameters on Scapulothoracic Joint Kinematics: Presentation of a Novel Shoulder Model

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**DISCLOSURES**: None

**INTRODUCTION**: The goal of any upper extremity shoulder treatment (operative and non-operative) is to restore function while alleviating pain. A major challenge in predicting outcomes for any given patient is that no tool exists that considers i) a patients existing shoulder function, ii) changes in muscle-tendon properties across the injury and recovery timespan contributing to shoulder function, and iii) neural control patterns for any given patient's preferred strategies for overhead reaching tasks (e.g., humeral and scapular control). Existing shoulder models do not model the shoulder as a closed-kinematic chain or use generalized coordinates that are difficult to personalize. We must improve modeling of the shoulder to aid clinicians in optimizing the best treatment option for each patient. The objective of this work was to develop a closed-chain kinematic model of the shoulder that accurately describes scapulothoracic and glenohumeral joint motions. We assessed the accuracy of this model by quantifying its ability to reproduce biplane fluoroscopy data across eight tasks.

**METHODS**: Experimental Data for this work consisted of patient-specific, high-resolution CT-images and biplane fluoroscopy kinematic data of the shoulder from an open-source repository[1]. Briefly, subject-specific 3D reconstructions of the scapula and humerus were created from CT-images and anatomical landmarks were identified for the scapula (glenoid center, GC; inferior angle, IA; trigonum spinae, TS; posterolateral acromion, PLA; acromioclavicular joint, AC) and the humerus (humeral head center, HHC; elbow lateral epicondyle, LE, and medial epicondyle, ME) using published methods[2]. Model-based markerless tracking was used with the biplane fluoroscopic data to generate accurate kinematics of the scapulothoracic joint and glenohumeral joint following standard Euler decomposition techniques to generate joint angles[3]. Activities assessed included a combination of weighted and unweighted overhead tasks during shoulder flexion, scaption, abduction, and internal/external humeral rotation (n=8 tasks).

Computational Model. A shoulder model was developed using standard joint types (e.g., hinge / ball-and-socket) enabling personalization of joint parameters—a major limitation of existing models. First, a subject-specific model was developed using model geometry described above within OpenSim (v4.4). The scapulothoracic joint was modelled with 5 degrees of freedom (DoFs) - 2 rotations about a spherical coordinate system, 1 translation about an intermediate body, and 2 additional rotations about a scapula-based rotation center (GC). The clavicle was attached to the thorax as a 2 DoF universal joint and to the scapula at the AC marker location as either i) a point constraint—producing a closed-chain kinematic shoulder model, or ii) an unconstrained joint where the clavicle was scaled to coincide with AC marker. The glenohumeral joint was modelled as a 3 DoF ball-and-socket joint (**Figure 1**).

To evaluate the kinematic accuracy of our shoulder model, we utilized a novel Joint Model Personalization (JMP) tool, part of the Neuromusculoskeletal Modeling (NMSM) Pipeline, to personalize joint parameters (positions/orientations), scale bodies, and move virtual markers. The tool takes user-provided settings to minimize the normalized mean squared distance between landmark and model markers on the scapula and humerus bodies using a bi-level optimization technique[4]. Each cost function evaluation used OpenSim's inverse kinematics solver through a Matlab API call (v2022b) to find the optimal model pose across all time frames given the current guess for the joint parameter values. All eight overhead tasks were used to personalize the shoulder models, where normalized mean squared distances were calculated between landmarks and model markers for constrained and unconstrained models.

**RESULTS**: On average across all tasks assessed, using the personalized joint parameters found by JMP led to greater accuracy for both the constrained (average error = 1.3mm) and unconstrained (average error = 1.1mm) models (**Table 1**). The largest error in tracking the anatomical, CT-based landmarks occurred at IA (9.8mm) for any given frame across all the tasks assessed (**Figure 2**).

**Table 1.** Average marker errors for constrained and unconstrained shoulder models

| Avg Marker Error (mm) | GC | IA | TS | PLA | AC | HHC | LE | ME |
|---|---|---|---|---|---|---|---|---|
| Constrained Model | 1.2 | 1.9 | 1.3 | 1.4 | 1.6 | 1.6 | 0.5 | 0.4 |
| Unconstrained Model | 0.7 | 2.2 | 1.4 | 0.9 | 1.3 | 1.1 | 0.6 | 0.6 |

**DISCUSSION**: The objective of this work was to develop a closed-chain kinematic model of the shoulder that accurately describes both scapulothoracic and glenohumeral kinematics. By personalizing the parameters of each joint, we were able to generate a kinematic model with average marker errors of approximately 1 mm, which outperforms a recent 4 DoF model employing a joint mobilizer (2 mm average error)[5]. The effects of constraining the shoulder at the AC joint—closing the kinematic chain—led to greater errors as compared to leaving the shoulder unconstrained for the optimization routine to parametrize and scale the clavicle relative to the acromion, but both models had an average error under 2 mm. The effects of constrained and unconstrained models on muscle-tendon paths and force transduction across the joint will be explored a future study. Our study is not without limitations. Our study only assessed model kinematics when calibrated with data from the same subject and requires testing with new motions. Additionally, we plan to validate kinematic motion of the clavicle in future work, which was assumed to act as a universal 2 DoF joint for this work. Lastly, we plan to introduce coordinate couplers to eliminate potentially one additional DoF at the scapula due to coupled motion between the clavicle and scapula. Despite these limitations, we have developed a model that allows for joint parameter personalization, which is critical for predictive modeling.

**SIGNIFICANCE**: We have developed a novel shoulder model that accurately measures the complex scapulothoracic and glenohumeral motions during overhead tasks. This objective, modeling based tool could be used to develop and test novel hypotheses related to treatment designs on resulting shoulder kinematic changes, which will drive forward the field of shoulder modeling and clinical care for shoulder patients.

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**REFERENCES**: [1] Kolz et al., J Biomech, 2021. [2] Kolz et al., Gait Posture, 2020. [3] Wu et al., J Biomech, 2005. [4] Reinbolt et al., J Biomech, 2005. [5] Seth et al., Frontiers Neurorobotics, 2019.

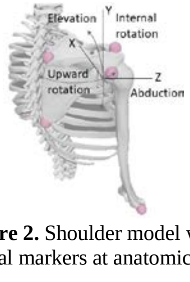


**Figure 2.** Shoulder model with virtual markers at anatomical

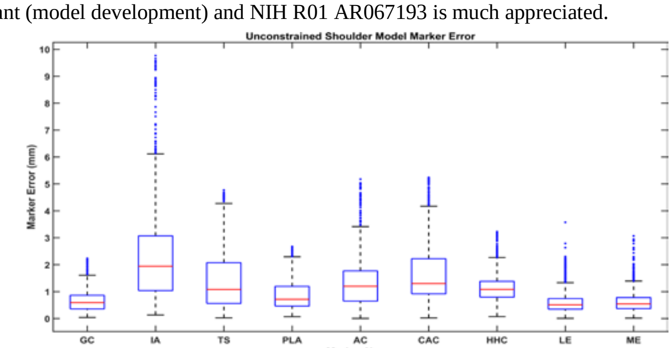


**Figure 1.** Individual marker errors of unconstrained AC joint across eight tasks