Morphological Characteristics of the Scapular Spine and Acromion that Predispose Reverse Total Shoulder Arthroplasty Patients to Post-Surgical Fracture

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INTRODUCTION: Acromion and scapular spine fractures occur in up to 10% of patients undergoing reverse total shoulder arthroplasty (RTSA) [1]. This complicated and unwanted problem arises due to increased stress in the acromion-process region of the scapula [2]. The RTSA procedure flips the ball and socket component, moving the center of rotation medially to create a longer lever arm to allow the deltoid to move the humerus. As a result, the deltoid must compensate by generating greater force, leading to an increase in deltoid and acromial stress of up to 60% and 37%, respectively [2]. Prior work has identified morphological characteristics as potential risk factors for acromion and scapular spine fractures following RTSA [3-5]. However, these studies were primarily limited to analysis of 2D imaging, dry bone, or cadaveric models that do not fully capture the complex 3D anatomy of living humans [3-5]. In this context, this study employs a statistical shape modeling (SSM) approach to analyze the 3D morphology of the scapula in patients following RTSA. We specifically tested the hypothesis that scapular morphology was different between individuals with RTSA who did versus those who did not sustain a fracture.

METHODS: Participants following RTSA were retrospectively identified from an IRB-approved databank to create fracture and control cohorts. A nearest neighbor algorithm was used to generate a 1:2 matching between cohorts based on age, sex, indication for surgery, and presence of inflammatory osteoarthritis. This yielded 18 participants with acromion or scapular spine fracture (5 male, 13 female) and 36 control participants (12 male, 24 female). Control participants were included if they showed no signs of fracture for two years post-RTSA. For each participant, the pre-operative scapula from the surgical side was segmented from CT images. Segmentations were smoothed using a Taubin smoothing algorithm. Left scapulae were reflected and treated as right scapulae. Statistical shape models were developed separately for the fracture and control cohorts in Shapeworks v.6.6.1. Briefly, scapulae were aligned using an iterative closest point algorithm and 13 anatomical landmarks were placed on each scapula to initialize the definition of the 2,048 correspondence particles used to generate reconstructed geometries. Mean shapes were defined for each cohort. Procrustes analysis was used to remove size variations as a confounding factor. A principal component (PC) analysis was then used to examine the modes of variation. Each PC (or mode of variation) represents a characteristic of shape variability, where the first PC captures the most variation and each subsequent PC captures less variation. Differences in the mean shapes (and the shapes representing ±2 standard deviations) of the fracture and control cohorts were evaluated using CloudCompare v.2.13.2. Analysis of surface deviations between each PC was developed by determining the deviations in surface distance of same PC between the control and fracture groups.

RESULTS: The first 12 PCs for the control and fracture models account for 88.2% and 93.9% of the overall shape variation, respectively. Comparison of the mean shapes shows relatively small surface deviations (-1.35 to 3.63mm) indicating subtle, but consistent shape differences between the fracture and control cohorts (Fig. 1). Along the scapular spine, the fracture cohort has a reduction of thickness and an increase in length of the acromion in comparison to the control cohort. Principal Component Analysis (PCA) of the first two PCs further highlights morphological differences between cohorts (Fig. 2). In PC1, the key morphological difference identified is the level of inclination of the scapular spine – the inclination steepness increases as the standard deviation becomes more positive. For the fracture model, as the standard deviation goes from -2 to +2, the base angle of the spine increases from 12° to 19°, while in the control model there is an increase from only 14° to 15° (Fig. 3A). Note, base angle of the spine was defined as the angle between the acromion, the base of the spine, and the midpoint of the posterior edge of the glenoid rim. PC2 revealed that as the standard deviations increased from –2 to +2 the greatest variation in shape is in the posterior–anterior length of the acromion with the fracture model having a range of length up to 17 mm versus 6 mm in the control (Fig. 3B).

DISCUSSION: The mean reconstructed shapes show population-wide morphological differences between the fracture and control cohorts. The less thick and more arched scapular spine in the mean shape of the fracture cohort likely reduces structural integrity, thereby predisposing the region to higher stress and increased fracture risk. The wide range of spine angle and acromion length in the fracture cohort also suggests that the scapular deltoid insertion point is more laterally positioned for at least some fracture patients. This lateral positioning could cause lever arm mechanics that produce greater moments, predisposing patients with this morphology to a higher fracture risk. However, further work is needed to fully understand patient-specific versus population-wide risk factors. Some limitations to this study include the small fracture cohort size, lack of consideration of bone quality, and the manual processing steps (anatomical landmark identification and segmentations). Further work will expand sample size, develop SSMs to determine whether scapular morphology varies between Levy fracture types, and evaluate to what extent morphological characteristics versus other clinical factors are predictive of fracture risk following RTSA.

SIGNIFICANCE/CLINICAL RELEVANCE: This study used SSM to identify population-level differences in scapular morphology between patients who did versus did not develop a fracture following RTSA. Understanding morphological risk factors is a critical step toward using SSM in the clinic for preoperative identification of at-risk patients and/or development of patient-specific surgical techniques aimed at reducing post-operative fracture incidence.

REFERENCES: [1] Mayne et. al. (2016) *Shoulder Elbow* [2] Patterson et. al. (2024) *J Shoulder Elb Arthoplast* [3] Yeazell et. al. (2021) *Shoulder Elbow* [4] Haidamous (2022) *Shoulder Elbow* [5]. Chen et. al. (2023) *Biomedical Signal Processing and Control.*

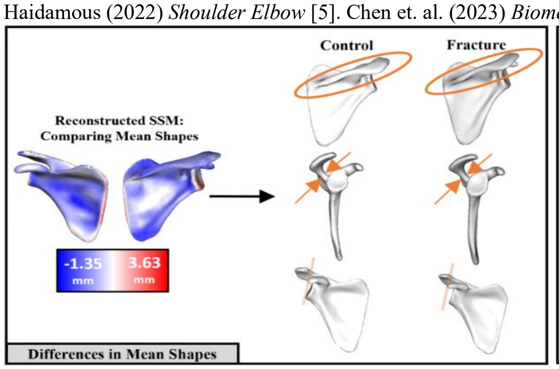

Fig 1. Morphological surface displacements (in mm; blue = inward, red = outward) of fracture versus control mean shapes including, spine curvature, spine thickness, and lateral acromion extrusion.

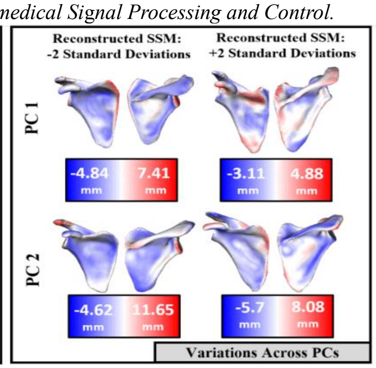

Fig 2. Morphological surface displacements using PCA of SSM reconstructions at ±2 standard deviations (in mm; blue = inward, red = outward).

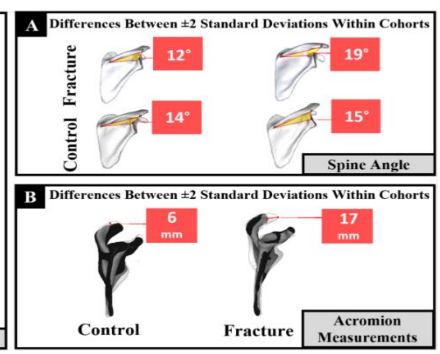

Fig 3. Scapular spine inclination (A) & acromion length (B) showed morphological variation in the fracture cohort versus the control cohort.