Patient-Specific Finite Element Modeling of Mechanical Forces within the Scapula Following Reverse Total Shoulder Arthroplasty

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Introduction: Scapular spine and acromial stress fractures are recognized complications following reverse total shoulder arthroplasty (rTSA). These complications occur postoperatively in approximately 5% of patients and are detrimental to patient outcomes and satisfaction. The rTSA implant reconfigures the shoulder joint mechanics by shifting the center of rotation (COR) laterally and inferiorly, enabling the deltoid to compensate for deficient rotator cuff function. However, this altered biomechanical environment increases deltoid tension and changes the force vector on the acromion and scapular spine, predisposing these structures to abnormal loading that can potentially lead to stress fractures. Moreover, the fracture repair and union in the region are challenging due to its thin geometry, typically poor bone quality, and difficulty in achieving immobilization. Herein, we describe the development of a patient-specific finite element (FE) model to characterize mechanical stresses experienced by the scapula following rTSA.

Methods: Muscle force vectors throughout shoulder abduction were obtained from an open-source shoulder mechanics model with the COR adjusted to match the patient's implant geometry. These forces were applied to an FE model of the patient's scapula which was segmented from preoperative CT scans with the FEBio software suite. Bone density and Young's modulus of bone were assigned to each element within the model using established equations correlating Hounsfield unit of the corresponding CT scan voxel to mechanical properties. Model reliability was confirmed through a mesh convergence study (<3% change in variables of interest) and a boundary condition sensitivity analysis performed using Dice similarity coefficient (DSC), Intraclass Correlation Coefficient (ICC), and Linear Mixed-Effects Model (LMM). Outputs included first principal (FP) stresses and FP strains extracted from Levy zones I–III, which were compared to the true fracture location on postoperative CT to assess predictive accuracy.

Results: Within the computational domain, all stress and strain metrics peaked during 10-20% abduction within the Levy II zone (see Figure 1; max/mean/min FP stress 34.587/4.363/-4.631 MPa; FP strain 0.00551/0.00127). As shown in Figure 2, FP stress was the most accurate predictor of fracture location when compared to a post-rTSA CT scan showing the patient's fracture, which served as a control against which the model was compared (max FP stress within approximately 1.25 mm, 3.2% of actual fracture location). Strain metrics were less reliable predictors (FP strain 33.392 mm, 55.1%). Between observers, there was excellent agreement based on the location of FP stress with a covariance of 1.67%. Sensitivity analysis results show observers produced consistent FE output patterns across load cases (ICCs ≈ 0.93–0.99); however, LMM detected systematic observer differences (p < 0.05), indicating significant interobserver variation in absolute outputs. Average similarity of boundary condition assignments was 0.653 between six users' inputs using pairwise DSC.

Discussion: These findings indicate that patient-specific FE modeling can reliably identify regions of elevated fracture risk within the scapula following rTSA, particularly through stress metrics. Such simulations and modeling may inform surgical planning, implant positioning, and postoperative rehabilitation strategies aimed at reducing scapular spine fracture incidence after rTSA. Sensitivity analysis demonstrated that although statistically significant observer variation existed in absolute model outputs for FP and effective stress based on alternative observer boundary condition assignments, there was no difference between observers on relative results between time-varied load cases, supporting the robustness of the model. Limitations to our current model include dependence on user-defined boundary conditions, mechanical property assignment assumptions derived from CT Hounsfield units, and validation using a single patient-specific model. Our future work will expand model validation across a larger cohort and refine boundary condition protocols to further improve reliability and generalizability.

Figure 1. Locations of maximum (red) and minimum (blue) FP stress within the scapular spine under peak loading conditions. Upper: posterior view of scapula, Lower: cross-sectional view at max stress from medial point of view, scale bar showing stress gradient in MPa.

Significance/Clinical Relevance:
Scapular spine and acromial stress fractures are a recognized complication following rTSA, yet the patient-specific changes to muscle force vectors resulting in complications remain poorly understood. This patient-centric FE modeling framework offers a novel, mechanistic approach to predict high-risk stress regions preoperatively, enabling improved surgical planning and implant placement to reduce fracture risk and improve patient outcomes.
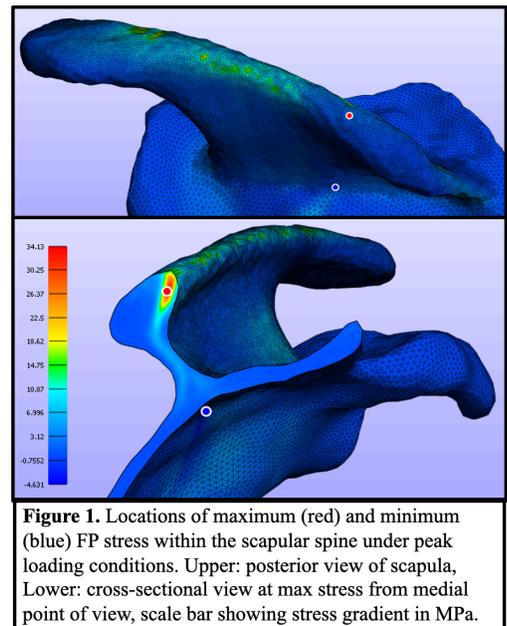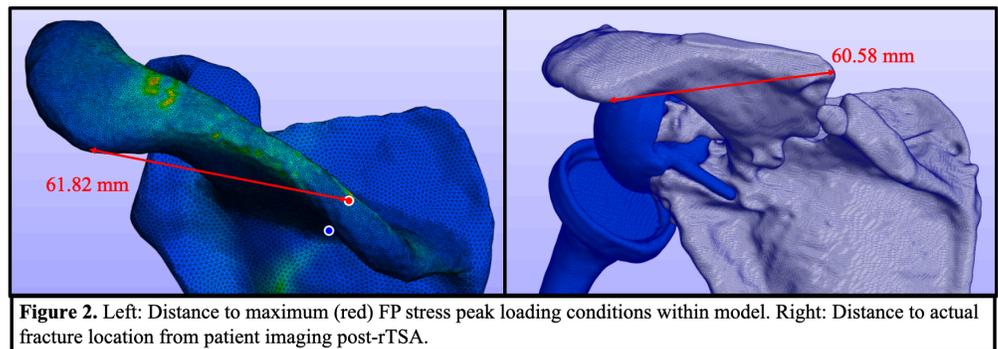

Figure 2. Left: Distance to maximum (red) FP stress peak loading conditions within model. Right: Distance to actual fracture location from patient imaging post-rTSA.