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Statistical Shape Models May Accurately Predict Subacromial Impingement of Shoulder Fractures in the Absence of CT Images

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Introduction

Proximal humeral fractures are a common injury and approximately 20% involve avulsions of the greater tuberosity (GT). Subacromial impingement occurs when a displaced GT fragment becomes wedged between the proximal humerus and the undersurface of the acromion, causing reductions in range of motion, intense pain, and a decrease in overall quality of life. It is difficult for clinicians to predict the likelihood of subacromial impingement, which requires surgical intervention to fix. CT images allow for the creation of patient-specific 3-D dynamics simulations capable of making estimates of impingement; however, CT imaging is typically not performed as a standard of care for proximal humerus fractures. In the absence of CT-rendered models of bones, statistical shape models (SSMs) may serve as reasonable surrogates for use in dynamic simulations of impingement. The goal of this experiment was to evaluate the predictive accuracy of SSMs by comparing specimen-specific outputs to models created with SSMs. We hypothesized that SSMs would be able to predict the occurrence of patient-specific subacromial impingement with at least 80% accuracy.

Methods

Twenty-three intact fresh-frozen upper extremity cadaveric specimens from 17 donors (8F, 9M; mean 81.6 y.o. range 74-89y.o.) were used in this preliminary study. Specimens were scanned with a clinical CT scanner using 0.5 mm axial slice thickness. Humeral and scapular geometries were segmented, flipped if needed to ensure all right-sided specimens, and aligned to the International Society of Biomechanics shoulder coordinate system. Simulated GT avulsions were made by slicing humeral heads in the sagittal plane, 8mm medial to the lateral-most point of the GT. Using a validated OpenSim shoulder model, passive range of motion tests were performed by sequentially simulating abduction from 0° to 180° (Figure 1A) at 18 different elevation planes between −90° (backward reaching) to 90° (forward reaching) (Figure 1B). ROM tests were repeated with all combinations of: 4 GT displacement magnitudes (2.5, 5.0, 7.5, 10.0 mm), 5 displacement directions (0° (anterior), 45°, 90° (superior), 135°, 180° (posterior)) (Figure 1C) and 4 fragment rotations (15°, 30°, 45°, 60°) rotated about the center of mass of the GT fragment along the sagittal axis (Figure 1D). For each of the 1440 unique simulations of abduction per specimen, a binary determination of contact between the GT fragment and the acromion was determined using the OpenSim elastic foundation contact model and 3D shoulder angles were recorded for each impingement event. The same 23 cadaveric specimens were then used as inputs to develop a statistical shape model (ShapeWorks) which output 5 humeral head and 5 acromion geometries, representing a mean shape, ±1standard deviation, and ±2 standard deviations (Figure 2A). All 25 combinations of SSM humeri and acromions were modeled to simulate the same dynamic abduction motions with variable injuries described above. Best-fit pairings of humeral and acromial SSMs for each of the 23 specimens were determined by finding the minimum differences in impingement predictions between SSM combinations and individual specimens.

Results

Best-fit SSMs predicted impingement events within the same elevation planes of CT-based models with 88.5±1.3% accuracy (range 83.2–93.7% for 23 specimens) (Ex: Figure 2B). The majority of subacromial contact events occurred when arms were performing abduction in the 30°-60° elevation planes (CT: 80.5%, SSM 82.4%). Predictions of the timing of impingement (abduction angle achieved before bony contact) only matched exactly 29.3±1.9% of the time. The average probability of impingement for the CT models was 4.3%, 6.8%, 12.4%, and 20.8% for GT fragment displacements of 2.5, 5.0, 7.5 and 10.0 mm, respectively. The probability of impingement for the SSM model was 9.1%, 16.7%, 25.8%, and 31.5% for the same displacements, indicating an overestimation, but similar progression of impingement as a function of displacement.

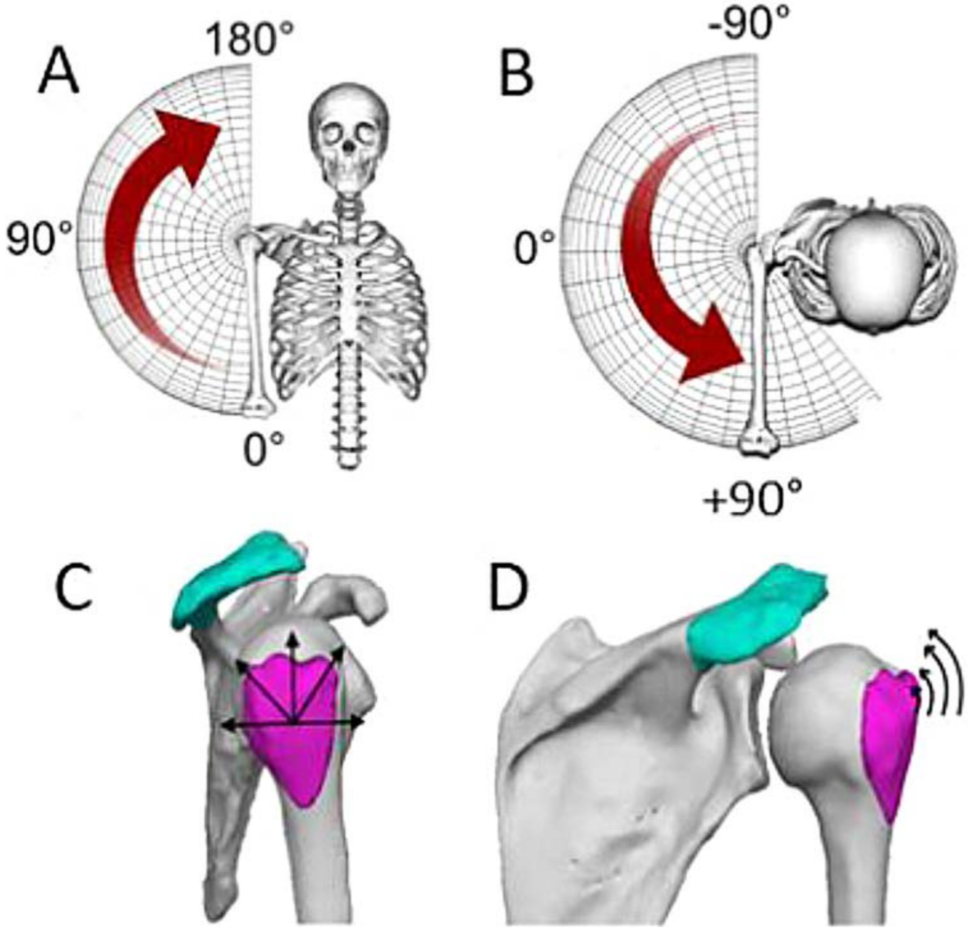

Figure 1. (A) Abductions were performed in **(B)** 18 elevation planes while GT fragments were **(C)** displaced and **(D)** rotated for a total of 1440 unique simulations.

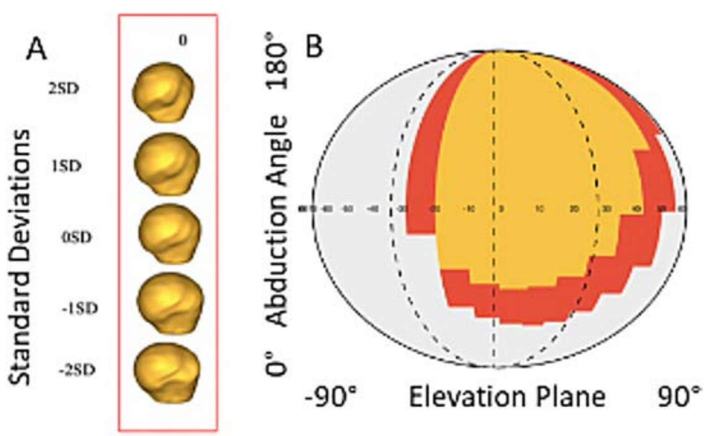

Figure 2. Statistical shape modeling generated **(A)** 5 unique humeral head geometries and acromion geometries (not shown); **(B)** Example of restricted range of motion (10mm displacement at 135o, 0o fragment rotation) shown on a sagittal plane hemisphere SSM models (red) overestimated impingement modeled with CT images (yellow).

Discussion

In accordance with our hypothesis, best-fit SSMs predicted impingement events of patient specific models with greater than 80% accuracy. This preliminary study provides confidence in using statistical shape models of bones as surrogates in dynamic musculoskeletal models. This study has limitations, as the ball joint used to represent the shoulder does not allow for compensatory translations of the humerus or scapula to avoid impingement. Future studies will increase the amount of training data for the SSM software, create algorithms that use 2D measures made on radiographs to assign 3D geometries within the SSM library, and incorporate images and patient-reported outcomes from living patients to further the accuracy and clinical relevance of the models.

Significance/Clinical Relevance

Accurate prediction of subacromial impingement of greater tuberosity fragments is difficult, but statistical shape models may enhance the limited data that is available with 2D radiographs. Continued development of simulations and algorithms capable of leveraging statistical shape models may improve standards of care without the need for CT imaging.