Shoulder Joint Modeling for Range of Motion Evaluation

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Abstract

Reverse total shoulder arthroplasty (rTSA) has increasingly become the solution for many seeking relief from immobility and pain. From 2011 to 2017, inpatient rTSA procedures increased over 190% with projections for 2025 reaching near 290,000 procedures [1]. This innovative design inverts the ball and socket of the shoulder joint, enabling stability and function for those with an irreparable rotator cuff (Fig. 1). The design of rTSA implants can result in an interference contact situation between the rim of the polymer "socket" liner on the humerus and the bone of the scapular neck, just inferior to the glenoid (the original anatomic socket). The interference manifests as "scapular notching," the removal of bone by the humeral liner rim, and consequently, gross liner rim wear. Study reports range from a 4% to 96% incidence rate of scapular notching associated with the use of rTSA, with the extent of contact being dependent on surgical placement and the implant system [2]. The goal of this project is to create a validated anatomic shoulder joint model to assess the effectiveness of range of motion (RoM) measures at detecting potential scapular notching conditions. Clinical RoM measures are standardized and well defined in anatomical planes. Requirements for the functional RoM of implants are conveyed in the Standard Specification for Shoulder Prosthesis (ASTM F1378-18). However, there is a disconnect between the clinical RoM of the shoulder, the functional RoM for shoulder arthroplasty devices as defined in ASTM F1378, and the natural RoM limits of a shoulder. Clinical and natural RoM data were acquired using a 10-camera 3D optical motion capture system (Vicon Motion Systems) [3]. Results from the model generation and validation will be presented, along with a comparison of the clinical and natural RoM assessments. By creating a better understanding of the differences between the clinical and natural RoM limits through modeling, we can work to improve shoulder standard specifications and rTSA implant performance.

Introduction

Reverse total shoulder arthroplasty (rTSA) was originally designed for people who no longer have a functional rotator cuff to hold the upper arm bone (the humerus) in place. A validated finite element (FE) model of the intact shoulder can help with the understanding of shoulder joint biomechanics and the implications of total shoulder arthroplasty.. An FE analysis can help identify risks associated with interactions between:

- Component-component
- Tissue-tissue
- Component-Tissue

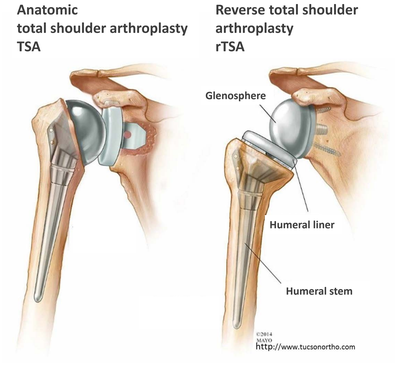


Figure 1. The design of the rTSA reverses the location of the ball and liner compared to the anatomic TSA, changing the interaction between components and hard (bone) and soft (cartilage, muscle, etc.) tissues.

Materials and Methods

Model:

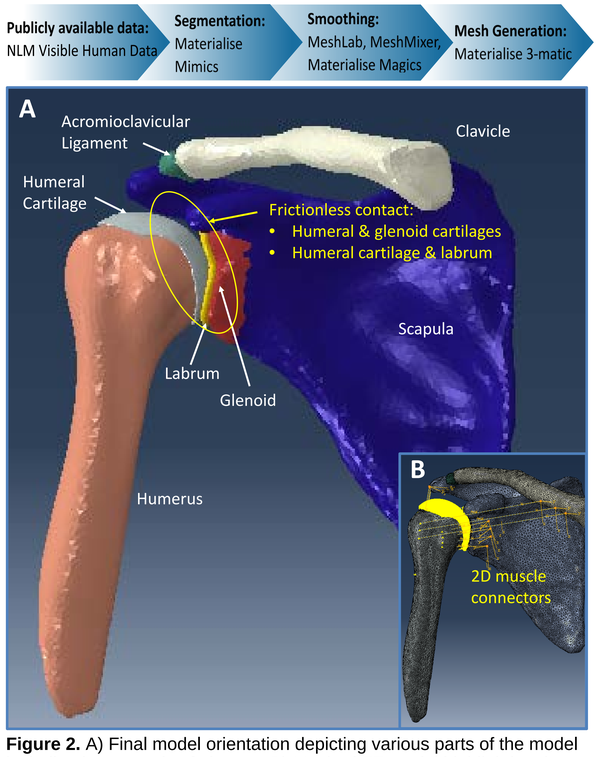
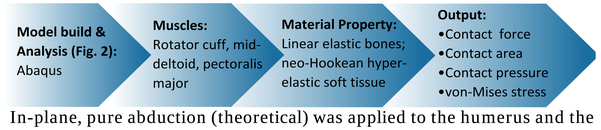


Figure 2. A) Final model orientation depicting various parts of the model including bones and soft tissues. B) Meshed FE model highlighting the interactions and muscle connectors.



In-plane, pure abduction (theoretical) was applied to the humerus and the contact force was extracted and compared to other studies. The FE model output mesh independence was demonstrated for an output variable convergence to 5% (Fig. 3). The model was validated against data published in the literature.

RoM: RoM limits were defined as a continuous sweep of the outer most limits of motion a subject's shoulder would allow them to reach. Data was collected using Bonita B10 optical cameras (Vicon™, Oxford, UK) and 33 reflective markers on the subject, including 6 dedicated to the scapula (Fs = 100 Hz). The subject repeated the RoM limits task 3 times. Data was then filtered, segmented, and trajectories of the humerus were calculated relative to the scapula (does not include the scapulothoracic movement).

Results

Model: The application of in-plane pure abduction to the model showed good agreement with the literature values, i.e., within one standard deviation from the mean value reported by in-vivo experiments for peak contact force. The peak contact force from our study was 747.83N which is in the range of force, 624.93±149.19N, reported from the in-vivo experiments of the six subjects analyzed by Bergmann et al. [4]. Also, contact force values at 0°, 10°, 20°, and 30° of abduction were in the range of other studies in the literature (Table-1). Based on the mesh convergence study (Fig. 3), an element count of 348,393 was used in the model.

RoM : Trajectories from the RoM Limits task illustrates how the humeral motion relative to the scapula along the perimeter of the range of motion differs compared to the typical in-plane theoretical abduction trajectory (Fig. 4). Removing contributions to the RoM Limits by scapular movement (scapulothoracic motion) truncated the limits along all axis.

Table 1. Glenohumeral contact force for the current study model and from the literature.

	Bone-on-bone contact force (N)			
Abduction Angle	0°	10°	20°	30°
Poppen et al., 1978	66	140	213	290
Bergmann et al., 2007	13	86	175	229
CURRRENT STUDY	84	90	137	212
Van der Helm et al., 1994*	5	66	125	176
Terier et al., 2008*	50	160	270	375
Favre et al., 2012*	30	100	215	450
Sins et al., 2015*	-	-	152	225
Zheng et al., 2019*	8	91	146	408

*computational study values

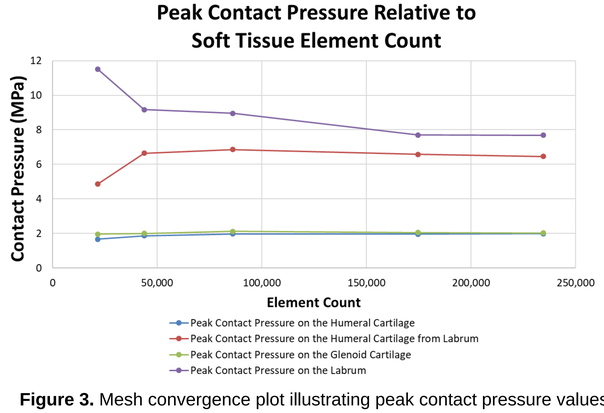


Figure 3. Mesh convergence plot illustrating peak contact pressure values on the cartilages and labrum vs element count.

References:
[1] Wagner, E.R., et al., JSES, 2020. 29(12).
[2] Friedman, R.J., et al., JAAOS, 2019. 27(6).
[3] Oliver, T., et al., ASB 2020 Conference, (Virtual) Atlanta, GA.
[4] Bergmann, G., et al., JBiomech, 2011. 44.

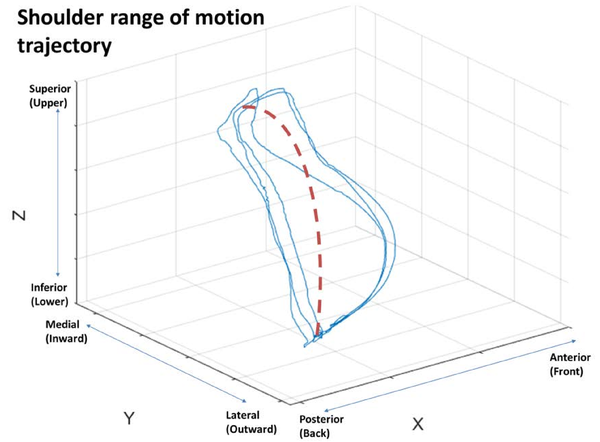


Figure 4. RoM measure comparisons. The blue trace represents the humeral motion relative to the scapula during the RoM Limits task (outermost natural limits of the shoulder joint motion path). The dashed red line is the theoretical 2D abduction/adduction motion path trajectory.

Discussion & Conclusion

This study created a validated finite element shoulder model based on public data while applying the principles of ASME V&V 40-2018 "*Assessing Credibility of Computational Modeling through Verification and Validation: Application to Medical Devices.*" The model was successfully validated with respect to glenohumeral contact forces during abduction. Future validation parameters are to include contact area, stresses and strains on the soft tissues and bones prior to investigating the effects of the RoM limits on these parameters. The final validated model will help with various shoulder biomechanical studies including implant design and investigation.

Limitations of this model include simplification of material properties, 2D representation of muscles, deriving the anatomy from one specific subject, and not considering scapulohumeral rhythm. However, these simplifications are consistent with previous studies and our validation demonstrated the effect of these limitations to be minimal.

Acknowledgments & Disclaimers

Human subject data for this study was collected under an FDA Internal Review Board (IRB) approved protocol.

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