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A Novel Workflow for Personalized Shoulder Modeling to Compute Glenohumeral Joint Loading in Shoulder Osteoarthritis and Anatomic Total Shoulder Arthroplasty Cohorts

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1. Introduction

Glenoid component loosening is a major complication following anatomic total shoulder arthroplasty (aTSA), with reported rates up to 44% (Gabriel et al. 2023). The rocking-horse phenomenon is considered the primary loosening mechanism, highlighting the value of investigating glenohumeral (GH) joint loading and shear forces to reduce loosening rates. Musculoskeletal modeling and simulations provide a valuable framework to analyze these loadings, which cannot be directly measured *in vivo*. Yet, models for GH osteoarthritis (OA) and post-aTSA patients remain limited, especially in terms of personalization.

This study introduces a workflow for personalized shoulder modeling that uniquely integrates humeral head (HH) translations to compute GH joint loading. The aim is to provide clinically relevant insights into how anatomical variations influence pre-aTSA loading and how surgical correction of glenoid version/inclination could reduce post-aTSA loosening risk.

2. Methods

2.1 Clinical dataset

Six OA patients scheduled for aTSA, with varying glenoid version and inclination, were selected from our prospective study. Within this study, we acquired pre-aTSA computed tomography (CT) scans and biplanar radiographs (EOS) in multiple arm poses—relaxed standing (RS) and 45/90° abduction (AB). CT-based bone models were registered to EOS images to determine 3D GH rotations and translations (Daneshvarhashjin et al. 2025).

2.2 Personalization pipeline

First, the generic thoracoscapular model (Seth et al. 2016) in OpenSim4.0 was adapted to include EOS-based GH translational degrees of freedom (DOF), and a refined scapular mesh, enabling personalization of muscle insertions and wrapping surfaces based on bone-morphing.

Second, this model was personalized through an automated pipeline which:

1. Scales the generic model based on each patient's HH diameter, while preserving the generic model mass.
2. Performs non-rigid morphing of the generic scapular mesh to the patient-specific geometry (MeshMonk, Matlab2023a).
3. Updates muscle insertions based on corresponding morphed scapular nodes.
4. Fits personalized wrapping surfaces to corresponding scapular nodes using Gauss-Newton optimization.

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This pipeline was used to create an average OA model (based on a statistical shape model of 64 OA scapulae), and 6 pre-aTSA personalized models with patient-specific geometries.

2.3 Joint reaction analysis

Following personalization, generic and EOS-derived patient-specific GH rotations and translations were applied to the average and personalized models, respectively. All models incorporated OA-based scapulohumeral rhythms to ensure correct scapular positioning (Spranz et al. 2019).

Next, muscle forces were computed using static optimization with reserve actuators for translational DOFs. GH joint reaction loads were obtained with OpenSim's JointReactionTool.

Spearman's rank correlation was used to assess relationships between glenoid version/inclination and GH loading direction.

3. Results and discussion

Pre-aTSA personalized total GH reaction forces increased with arm abduction (Fig.1C). This association was primarily driven by increasing muscle activity to counteract gravity and stabilize the joint.

Superior shear forces also increased with abduction (Fig.1B), likely reflecting additional muscle contributions to resist downward gravitational pull, consistent with previous findings (Bergmann et al. 2011). In contrast, horizontal shear forces showed large directional variability across patients and arm poses (Fig.1A).

Posterior shear force directions correlated with glenoid retroversion across all poses, while superior force directions correlated with superior inclination (Table 1). These relationships suggest that increased version/inclination reduces GH stability and increases eccentric loading, confirming that centralizing GH loading is a critical aim in aTSA planning to lower loosening risk. However, all results should be interpreted cautiously given our small sample size.

Table 1. Spearman's rank correlations (R) between glenoid version/inclination and force direction.

Arm pose	R(version~ horizontal shear)	R(inclination~ vertical shear)
RS	0.71 (p=0.09)	0.36 (p=0.44)
45AB	0.39 (p=0.4)	0.43 (p=0.35)
90AB	0.6 (p=0.35)	0.9 (p=0.08)

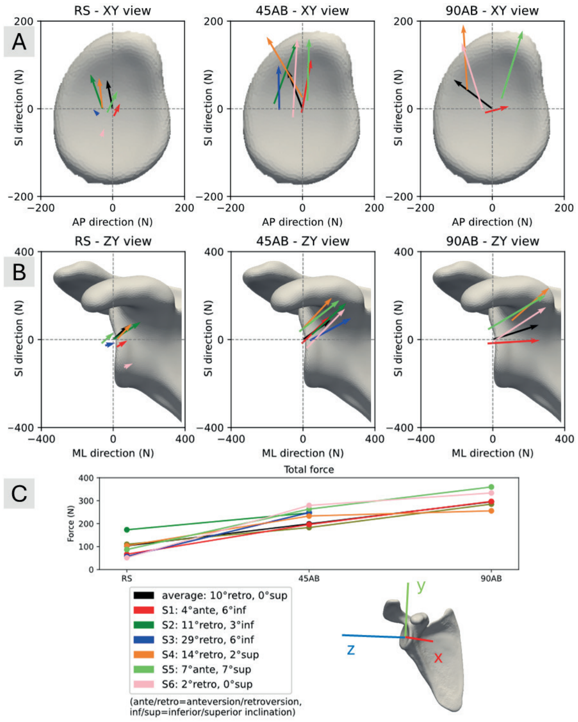

Figure 1. Total GH reaction forces in abduction poses (C), visualized in glenoid (A) and perpendicular (B) planes. Contact locations, considered equal to HH translations, are normalized to patient-specific HH radii. Scapular coordinate frames: X- and Y-axes orthogonal to scapular and transverse plane, respectively; Z-axis mutually orthogonal. AP:anteroposterior/horizontal shear, SI:superior-inferior/vertical shear, ML:mediolateral/compression.

4. Conclusions

These preliminary findings demonstrate feasibility and clinical potential of a novel workflow for personalized shoulder modeling and GH loading estimation. By incorporating patient-specific geometry and HH translations, this workflow enables personalized loading predictions, as reflected in force pattern variability.

The link between glenoid version/inclination and loading direction highlights the need for accurate aTSA implant positioning to reduce postoperative subluxation risk and prevent excessive eccentric loading—a key contributor to glenoid loosening. Future work will analyze our available cohort of 33 patients in pre- and post-aTSA configurations up to 120° abduction, assessing whether the rocking-horse phenomenon occurs post-aTSA and can be predicted preoperatively.

Conflict of Interest Statement

None.

Contributor Roles

LV: Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Software, Validation, Visualization, Writing original draft, Writing – review & editing; ND: Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Project administration, Writing – review & editing; PD: Conceptualization, Data curation, Funding acquisition, Investigation, Project administration, Resources, Supervision, Writing – review & editing; FV: Conceptualization, Data curation, Funding acquisition, Investigation, Project administration, Resources, Supervision, Writing – review & editing; LS: Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision, Writing – review & editing.

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