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Patient-Specific Reconstruction of Shoulder Anatomy Driven by Radiographic Anatomical Parameters Using Statistical Shape Modelling

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1. Introduction

The complex anatomy of the shoulder exhibits substantial inter-individual variability, strongly influencing joint biomechanics and muscle mechanics (Silvestros et al. 2024). In clinical practice, shoulder morphology is routinely described using standardized radiographic clinical morphological parameters (CMPs) of bone geometry. However, current musculoskeletal models typically rely on generic anatomies or require time-consuming segmentation and point correspondence from 3D imaging (Cates et al. 2017).

This study aimed to develop and evaluate a statistical shape model (SSM) reconstruction pipeline for patient-specific 3D bone models of scapula and humeral head from a limited set of 2D CMPs.

2. Methods

2.1 Data

The dataset consisted of 128 shoulder shapes, derived from MRI segmentations of the scapula and humerus in healthy subjects and patients with symptomatic or asymptomatic rotator cuff tears (Croci et al. 2026). The study was approved by the regional ethics board (Ethics Committee Northwest Switzerland EKNZ 2024-01940). The SSM was generated using 80% of the dataset, the remaining 20% were used for validation. Key CMPs were obtained on all shapes based on manually labeled anatomical landmarks to provide ground-truth measurements. The model parameters included glenoid version (GV), glenoid inclination (GI), critical shoulder angle (CSA), lateral acromion angle (LAA), acromial slope (AS), acromial index (AI), acromial tilt (AT) and the ratio of the glenoid width over the humeral head radius (GW/HH) (Verhaegen et al. 2021).

2.2 SSM and optimization

Particle-based correspondence across all shapes was established using ShapeWorks (Akhundov et al. 2022). The humerus and scapula were represented by 1024 and 4736 corresponding particles, respectively. Shapes were aligned and scaled using Generalized Procrustes Analysis prior to Principal Component Analysis (PCA) to capture the main modes of anatomical variation.

Patient-specific reconstruction was performed by optimizing the PCA shape coefficients of the MRI-derived SSM using sequential least-squares programming, such that the CMPs of the reconstruction match the CMPs of the ground-truth models.

At each iteration, reconstructed CMPs were updated by tracking the particles corresponding to CMP landmarks defined on the SSM mean shape.

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The optimization model minimized the following loss function.

$$L = \sum_i w_i \left(CMP_i^{recon} - CMP_i^{target} \right)^2$$

2.3 Validation

The known CMPs were used as target inputs for the optimization model. Reconstruction performance was quantified by computing the absolute error of radiographic parameters between the original and optimized shapes, the mean Hausdorff distance across all reconstructed shapes, and the root mean square error (RMSE) of particle positions.

3. Results and Discussion

Table 1. CMPs absolute reconstruction error.

CMPs	Mean error ± std	Max error
GV (°)	0.1 ± 0.2	0.7
GI (°)	0.1 ± 0.2	0.8
CSA (°)	<0.1 ± 0.1	0.5
LAA (°)	0.3 ± 0.8	3.1
AS (°)	0.2 ± 0.5	2.4
AI	0.001 ± 0.002	0.009
AT (°)	<0.1 ± 0.2	0.8
GW/HH	0.002 ± 0.006	0.019

Credit: Mareschal.

The mean reconstruction error to the target CMP was ≤0.3±0.8° for all angular parameters and ≤0.002 for AI and GW/HH ratio (Table 1). Across all shapes, we obtained a mean Hausdorff distance of 14.7±6.9mm. Surface-to-surface similarity was lowest in the superior angle of the scapula, along the scapular spine, and at the medial border in most shapes.

Figure 1 shows the spatial heterogeneity of RMSE between particle positions of target and reconstructed shapes. Regions constrained by input parameters, such as the glenoid, acromion and humeral head, exhibited the lowest errors (≤4.2 mm). Higher RMSE values were observed in areas less represented by parameters including the superior angle of the scapula (9.8 mm), the scapular spine (7.3 mm) and the coracoid process (5.6 mm).

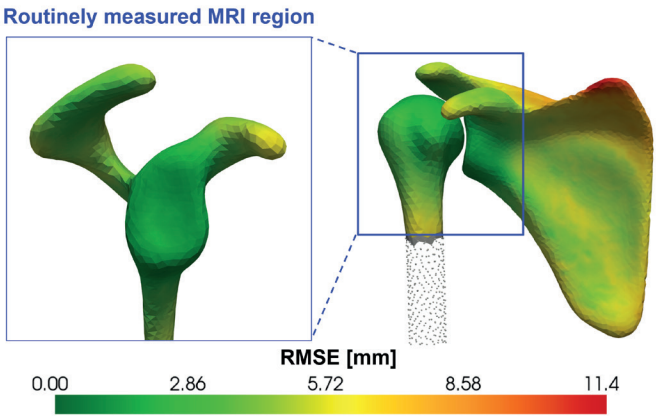

Figure 1. Mean reconstruction RMSE projected onto the 3D mean shape.

Credit: Mareschal.

The reconstruction pipeline effectively reproduced the CMPs in anatomically and biomechanically relevant regions. The low RMSE in the glenoid and acromion corresponded mostly to areas constrained by the CMPs and thus of primary interest. Higher errors in above-mentioned regions reflected the current limitations of CMP-driven reconstruction.

4. Conclusions

We demonstrated that patient-specific shoulder geometries can be accurately reconstructed from a limited set of routinely measured radiographic parameters. Because MRI-derived CMPs are measured in the projected true anteroposterior and scapular Y-view planes, the method should be transferable to standard X-ray projections. The method reliably reproduced the overall shapes, particularly in clinically relevant regions, such as the glenoid and acromion. Areas less represented by parameters, such as superior angle and scapular spine, show larger errors. Although these regions are expected to have limited influence on musculoskeletal simulation outcomes, they may be less suitable for analyses requiring detailed local geometry. For routine modelling applications, 3D reconstructions derived from standard CMPs may suffice without the need for further complex analyses. This reconstruction pipeline will enable integration into computational models for the study of shoulder biomechanics and pathology, with potential applicability in clinically relevant workflows. With further refinement and additional input parameters, the approach will have the potential to support clinicians in patient-specific surgical planning.

Conflict of Interest Statement

None.

Contributor Roles

LM: Methodology, Formal analysis, Visualization, Writing original draft; JG: Conceptualization, Methodology, Visualization, Funding acquisition, Supervision, Project administration, Writing-review & editing; EC: Resources, Conceptualization, Data collection, Writing-review & editing; AM, BD: Conceptualization, Methodology, Funding acquisition, Supervision, Writing-review & editing; DG: Conceptualization, Methodology, Funding acquisition, Writing-review & editing; ECD: Methodology, Funding acquisition, Writing-review & editing; AS&AMM: Conceptualization, Supervision, Writing-review & editing.

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