2026-3 | International Shoulder Group (ISG) Congress 2026
2-3 June 2026, Lyon, France

Multidisciplinary Biomechanics Journal

Volumetric Muscle Modelling for Physiological Testing of the Glenohumeral Joint

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Received date: 16/01/2026
Accepted date: 16/03/2026
Publication date: 02/06/2026

Keywords: biomechanics, glenohumeral joint, muscle forces

1. Introduction

Accurate Glenohumeral (GH) simulation is challenging because the glenoid covers a small portion of the much larger humeral head, hence stability depends strongly on soft tissue and fine coordinated action of an over-actuated muscle system. As highlighted in the review by Genter et al. (2023), there is scope for improvement of existing GH joint simulators.

A key limitation is the modelling of the deltoid. Most simulators implement cable-based actuation, which either neglect the deltoid volume or run cables over the entire volume of cadaveric deltoids, as seen in the review by Genter et al. (2023).

Modelling deltoid volume improves physiological moment arm accuracy, enhancing GH simulation fidelity with easier testing than with cadaveric deltoids, advancing shoulder mechanics understanding.

This study developed a volumetric deltoid muscle model for a GH joint simulator and assessed its influence by comparing the forces required to achieve predefined abduction angles with a conventional cable-based actuation approach.

2. Methods

2.1 Mechanical system

2.1.1 Deltoid model

The deltoid model was manufactured from silicone cast into a custom 3D printed mould, with the geometry derived from one MRI scan (Genter et al., 2024). The deltoid was modelled with seven muscle portions grouped into anterior, middle, and posterior groups. The anterior and posterior groups each comprised two portions, while the middle group comprised three portions. The muscle path of each portion was achieved by positioning a Bowden cable along the midline of the corresponding muscle segment, with the hollow outer cable housing embedded within the silicone.

2.1.2 Scapula and Humerus model

The geometry of the scapula and humerus was derived from a CT scan corresponding to the MRI data used for the deltoid (Genter et al., 2024). The bone models were modified to incorporate insertion points for the actuation cables of each muscle portion, as well as adapters for integration with the GH simulator and prosthetic components, and were subsequently 3D printed. A prosthetic GH joint with CoCr surface was used to minimise friction within the experimental setup.

2.1.3 Integration of the model on a GH Simulator

The deltoid, scapula, and humerus models were implemented in an in-house GH simulator (Genter et al., 2023), which uses motor-actuated cables to simulate muscle-driven joint motion. EC motors (Maxon, Switzerland) tensioned muscle groups, with forces measured via load cells (Interfaceforce, Germany), abduction angles measured with an IMU (Tinkerforge, Germany), and joint reaction force (JRF) recorded using a six-degree-of-freedom load

To cite this article: Molly Abraham, Jeremy Genter, Maria Grazia Polizzotto, Federico Andrei, Linda Paternò, Daniel Baumgartner, Volumetric Muscle Modelling for Physiological Testing of the Glenohumeral Joint, *Multidisciplinary Biomechanics Journal*, 2026, vol. 3, p. 97–99, DOI: 10.46298/mbj.17940.

cell (Transmetra, Switzerland). To model arm inertia, a 2.8 kg mass was attached to the humerus at 23 cm from the humeral head centre.

Each EC motor was connected to a pulley system distributing force equally to the muscle portions. From the pulleys, cables ran through scapular insertion points, wrapping over the humerus and through the volumetric deltoid model when applicable, to the humeral insertion points (Figure 1).

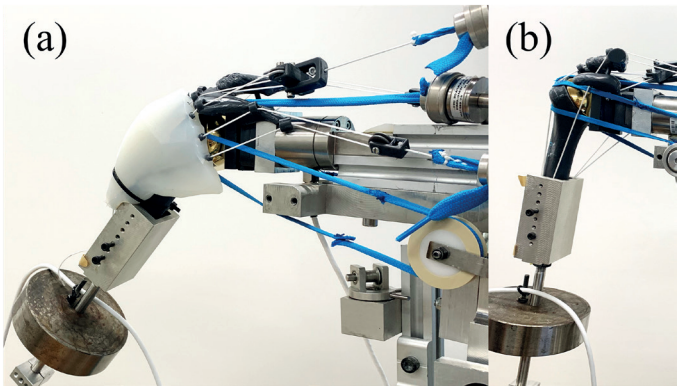

Figure 1. (a) Posterior view of abducted shoulder with volumetric deltoid model. **(b)** Anterior view of relaxed shoulder with cables wrapping over humerus.

2.2 Proof of concept testing

To validate the developed deltoid muscle model, forces in the middle and anterior deltoid muscle groups were measured under static conditions at predefined shoulder abduction angles, 15°, 30°, 45° and 60°, achieved by first increasing the force to achieve 60° and slowly reducing to achieve the specified abduction angles. As only abduction was of interest, the posterior deltoid was not tensioned. Equal forces were applied to both actuating deltoid muscle groups.

The measurements were replicated without the volumetric deltoid model, with the actuation cables wrapped directly over the bone. Three repeats were done for each setup.

3. Results and discussion

Integration of the volumetric deltoid model in the GH simulator altered the force–abduction relationship (Table 1), with muscle forces and JRFs required for a given abduction up to 75% lower than in the wrapped cable configuration. Without stabilisation from the volumetric deltoid, full abduction was not reached.

Table 1. Force applied in the middle/anterior deltoid and corresponding JRF to achieve abduction angle, n=3.

Angle (°)	Average Muscle Force (N)		Average Joint Reaction Force (N)	
	Silicone	Wrapped cables	Silicone	Wrapped cables
15	39±3	82±8	55±6	142±21
30	77±4	117±5	142±8	207±11
45	107±3	148±2	193±5	257±3
60	143±5	-	239±7	-

Measured JRFs were comparable to in vivo measurements of 207 (60) N at 30° (Bergmann et al., 2011). Our muscle force measurements were in a similar range to the ex vivo measurements from Ackland et al. (2011), of 104 (21) N at 30° in the middle deltoid and 11 (2) N in the anterior deltoid, where actuating cables ran over cadaveric deltoids.

4. Conclusions

Incorporating a volumetric deltoid model in a GH joint simulator improves accuracy by replicating physiological muscle moment arms in comparison to cable over bone or cadaveric deltoid setups. 3D printed components allow for personalisation of the experiment. It is seen that by increasing the deltoid moment arms, forces required for abduction can be reduced, therefore, cable-driven simulators wrapping over the humerus or deltoid might over or underestimate deltoid forces. Further tests could include the effect on rotator cuff contribution and incorporation of a more refined muscle force solver.

Acknowledgements

This work was done in collaboration between the Institute of Mechanical Systems (IMES) at Zurich University of Applied Sciences (ZHAW) and the BioRobotics Institute at Sant'Anna School of Advanced Studies in Pisa, Italy. We would like to thank the EELISA network for the collaboration opportunity.

Conflict of Interest Statement

None.

Funding

ZHAW internal funding with additional support of the EELISA alliance for travelling & exchange.

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