Human Shoulder Finite Element Model ReadMe

Sara Sadeqi,1,2 Andrew P. Baumann,2 Vijay K. Goel,1

Victoria Lilling,3 and Stacey J. L. Sullivan2

1Departments of Bioengineering and Orthopaedics, Engineering Center for Orthopaedic Research Excellence (E-CORE), The University of Toledo, Toledo, OH, USA; 2Center for Devices and Radiological Health, Office of Science and Engineering Laboratories, Division of Applied Mechanics, U.S. Food and Drug Administration, 10903 New Hampshire Avenue, Building 62 Room 2210, Silver Spring, MD 20993, USA; and 3Center for Devices and Radiological Health, Office of Product Evaluation and Quality, OHT6: Office of Orthopedic Devices, DHT6A: Division of Joint Arthroplasty Devices, Shoulder Arthroplasty Devices Team, U.S. Food and Drug Administration, Silver Spring, MD, USA

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**Background**

A finite element model of the male human shoulder was created. The model is a first step in developing a validated computational framework for researching the biomechanics of the human shoulder. The model is provided, here, in its entirety. The included inp and cae files (Male-Shoulder.inp, and OpenSourseShoulderFE.cae) contain the finite element model, as constructed in Abaqus/Explicit 6.14-5. The model simulates abduction of the shoulder joint in the scapular plane. Simulation outputs include contact forces and stresses.

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Output data are provided for comparing to outputs generated by simulations on other hardware/software systems to ensure functionality of the model.

**Model Components**

The model (Figure 1) includes 3D geometries meshed with C3D10 elements for the following tissues: Humerus, Scapula, Clavicle, Humeral cartilage, Glenoid cartilage, Labrum, and Acromioclavicular ligament.

2D connector elements with tension loads are used for muscle-tendon units of the following muscles: rotator cuff (Supraspinatus, Infraspinatus, Subscapularis, and Teres minor), Mid-Deltoid, and clavicular head of the Pectoralis Major.

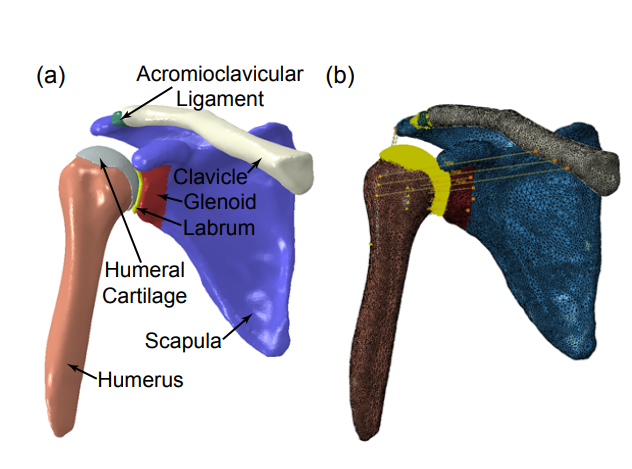


Figure 1) (a) Model of the intact shoulder in Abaqus displaying the different bones (humerus, clavicle, scapula, and glenoid) and soft tissue (humeral and glenoid cartilages, AC ligament, and labrum) components. (b) Meshed view of the model depicting interactions and muscle 2D connectors.

**Component Geometry**

Humerus, Scapula, Clavicle, labrum, and Acromioclavicular ligament were manually segmented from CT scans of the visible human project male subject in Mimics 19. The glenoid cartilage and humeral cartilage were made by offsetting the mesh layers in Abaqus to reach the thickness of these cartilages as mentioned in the literature [1, 2].

**Material Properties**

Material properties of the model (Table 1) include linear elastic for the bones (humerus, scapula, and clavicle) and Neo-Hookean hyper-elastic for the soft tissue (Glenoid cartilage, humeral cartilage, labrum, and Acromioclavicular ligament). Portions of the bones away from the areas of interest (humeral shaft, scapula body, and medial clavicle) were modeled as rigid bodies for computational efficiency. Values from the literature were applied to the all the model components.

Table 1) Material properties of different components of the model.

|  |  |  |  |
| --- | --- | --- | --- |
| Anatomy | Material Type | Parameters | Reference |
| Scapula | Linear Elastic | E=16 GPa, ν=0.3 | [3] |
| Humerus (Cortical Bone) | Linear Elastic | E=12 GPa, ν=0.3 | [4] |
| Humerus (Cancellous Bone) | Linear Elastic | E=250 MPa, ν=0.3 | [4] |
| Clavicle | Linear Elastic | E=17 GPa, ν=0.3 | [5] |
| Glenoid | Linear Elastic | E=1.4 GPa, ν=0.3 | [6] |
| Acromioclavicular (AC) Ligament | Hyper-elastic | C10=1.125 MPa, D1=0.19 | [7] |
| Glenoid Cartilage | Hyper-elastic | C10=1.79 MPa, D1=0.12 | [8, 9] |
| Humeral Cartilage | Hyper-elastic | C10=1.79 MPa, D1=0.12 | [8, 9] |
| Labrum | Hyper-elastic | C10=12.5 MPa, D1=0.017 | [10] |

**Interactions**

Surface-to-surface interactions with finite sliding (tangential behavior: penalty, coefficient of friction=0.01, normal behavior: “Hard” contact pressure-overclosure) were applied to the contacts between humeral and glenoid cartilages and between humeral cartilage and labrum. Tie constraints were used for connecting humeral cartilage to the humeral head bone, glenoid cartilage to the glenoid bone, and the ends of the acromioclavicular ligament to the clavicle and acromion.

**Steps, Loads, and Boundary Conditions**

The model consists of two Dynamic, Explicit steps. In the first step, a compressive displacement boundary condition (BC) of 0.8 mm was applied in the z direction of the glenohumeral joint axis (LOADAXIS) to bring the humeral and glenoid cartilages in contact. In the second step, 100о abduction rotational BC was applied over the y axis of the LOADAXIS coordinate system. Other degrees of freedom in the model were fixed. Muscle forces were also applied in the second step via connector force with amplitudes from the literature. The abduction was used to validate the model outputs against in vivo experiments [11, 12] and compare with other simulations [13-17] which modeled abduction.

**Mass Scaling**

Mass scaling may be used in Abaqus/Explicit analyses to increase computational efficiency with the potential consequence of decreased accuracy. To choose a proper mass scaling for this model, the energy outputs were monitored to make sure they satisfy the energy balance criteria mentioned in the Abaqus documentation (Abaqus 6.14 user manual, sec. 6.3.3).

**Outputs**

The main output of the model is glenohumeral contact force. However, other outputs such as stress, strain, contact area, and contact pressure can also be extracted from the model.

**Verification**

Simulation outputs are provided in the added spreadsheet. Users are encouraged to compare these outputs to those generated on their software/hardware.

**Runtime**

The time for the simulation to complete was approximately 15, 17.5, 22, and 23 hours for 84cpus-single precision, 8cpus-single precision, 84cpus-double precision analysis, and 84cpus-double precision analysis and packager, respectively.

**Additional Information**

Full details on the development of this model are published in Annals of Biomedical Engineering: <https://link.springer.com/article/10.1007/s10439-022-03018-8>.

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