A MODEL OF GLENOHUMERAL STABILIZATION

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SUMMARY

In this study, we present the first finite element model of the glenohumeral joint to implement realistic, active muscle driven positioning of the humerus, without relying on *a priori* imposed kinematic constraints. This model relies on both novel and established methods to simulate joint balance and stabilization through muscular action in any joint position.

INTRODUCTION

The glenohumeral (GH) joint is the most frequently dislocated major joint of the body. GH stability is primarily ensured by active muscular contraction, and the sheer complexity of the joint has restricted elucidation of the stabilization mechanisms. Due to this complexity, simplified modeling approaches are of limited use. Although realistic (anatomically precise) models of the GH joint are clearly required, validated six degree of freedom (DOF) models have not been described, and *a priori* restrictions of glenohumeral kinematics have been widely employed. The purpose of this study was thus to develop a robustly validated three-dimensional (3D) numerical model of GH joint stability enabled by musculature.

METHODS

The model consists of the integration of three key steps (Figure 1), each of which can be performed automatically for any instantaneous (treated as static) joint position, which can be viewed as a "snapshot" of a larger dynamic movement (if inertia is neglected).

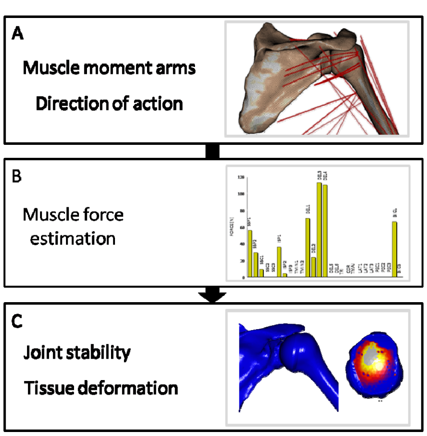

Figure 1: Integrated model architecture based on three steps.

First, the muscle moment arms and lines of action were computed for an instantaneous position of interest (Fig.1A) using a recently developed automated wrapping method [1]. The 3D anatomy of a human scapula and humerus were reconstructed and imported as rigid bodies into a finite element (FE) modeling software to compute the muscle path for 27 muscle segments, represented as deformable strings.
Second, the muscle moment arms and lines of action computed in the preceding step were used in an algorithm [2] to estimate forces in each individual muscle segment adequate to balance a given external moment (Fig.1B). If joint stability (defined as the ratio of shear component of the resultant force divided by the compressive component) was less than a critical threshold, supplementary rotator cuff activity was incrementally applied until the joint was stabilized.
Finally, resultant force derived by the algorithm was applied within an anatomically precise 3D FE model of the GH joint for simulation of joint contact and humeral head translation (Fig.1C). The humeral and scapular geometries were meshed with quadratic tetrahedral elements and defined as isotropic linear-elastic. The geometry of the cartilage and labrum were created on the basis of published anatomical data and hyperelastic neo-Hookean incompressible material properties were defined. The ligamentous capsule was not modeled. The medial part of the glenoid and the humerus were initially fixed in translation and rotation. All degrees of freedom of the humeral head were then progressively released until it was completely free to rotate and translate within the glenoid, and centered by the compressive component of the resultant force only. The shear resultant force component was then added, and the model was permitted to assume its "natural" configuration.
This approach was validated against experimental data pertaining to 0 to 80° GH elevation. An arm weight of 35N was applied and elevation was simulated as a succession of 10° incremental steps. The resulting muscle moment arms, muscle on-off activity, joint contact forces and humeral head translations during motion were validated against a broad range of previously reported experimental measurements.

RESULTS AND DISCUSSION

The integrated model solved for the simulation of one instantaneous position on a standard desktop PC in less than three hours.

A remarkable aspect of this model was its success in organically predicting a wide range of experimental data without artificial tuning of the model. Predicted muscle on-off activity patterns, muscle moment arms, and humeral head translations (Figure 2) were all consistent with reported experimental values. Joint contact forces (Figure 3) were also comparable to values previously published in modeling studies and in vivo measurements.

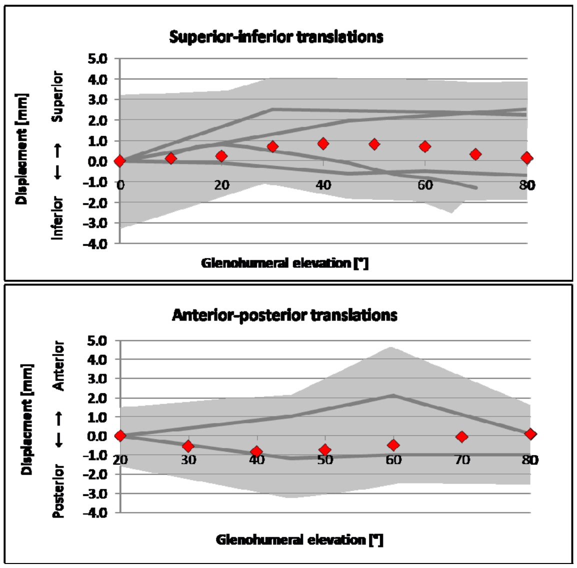

Figure 2: Simulated inferior-superior (top pannel) and antero-posterior (bottom) translations of the humeral head during elevation in the scapular plane (red). The grey curves represent the mean reported experimental values and the shaded gray area spans the plus-minus standard deviation range.

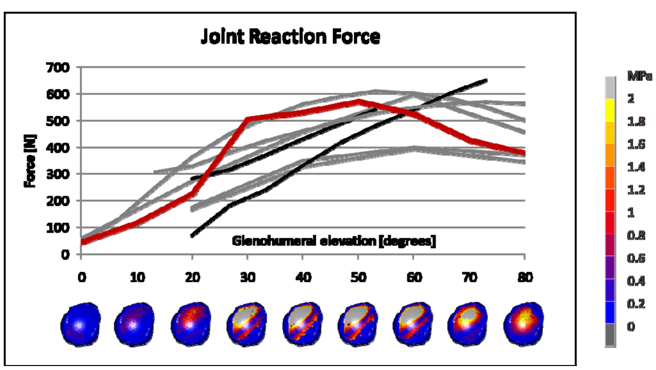

Figure 3: Simulated joint reaction force (red) during GH elevation in the scapular plane. The grey curves represent the reaction forces obtained in other modeling studies, and the black curves represent in vivo recorded values in two patients by means of a telemetric implant [6].

Substantial supplementary rotator cuff activity was required to provide adequate stability between 30 and 50 degrees GH elevation (Figure 4), while for the rest of motion, muscle forces estimated by the algorithm were adequate to automatically center the joint.

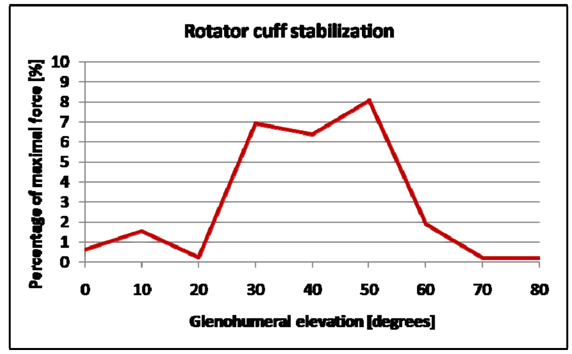

Figure 4: Supplementary force exerted by the rotator cuff to stabilize the GH joint during elevation.

This model demonstrates that during elevation, GH joint stability can theoretically be achieved exclusively through muscular activity. For most simulated GH positions, the predicted muscle forces automatically centered the joint without substantial rotator cuff activity. This emphasizes the fact that an optimal coordination of muscular activity can guarantee joint stability, and suggests that sensorimotor alterations could contribute to deficits in functional stability. This supports surgical interventions and rehabilitation strategies that not only repair the mechanical constraints that have been disrupted by injury, but also aim at restoring the structures responsible for sensorimotor control of joint stability [4,5].

CONCLUSIONS

This is the first numerical model of the GH joint that does not rely on artificial kinematic constraints, and is able to maintain joint stability through active muscular contraction. Realistic 3D joint behavior was predicted for full GH elevation. Muscle moment arms, muscle forces and joint contact characteristics could be computed automatically at any joint position, with a composite of instantaneous positions enabling simulation of a dynamic motion.

This validated model integrates muscle wrapping, muscle recruitment, and deformable joint movements to provide a platform that can be used to investigate important unsolved questions in shoulder biomechanics and surgery. While the lack of a modeled capsule may limit predictive capacity at extreme ranges of motion (remaining grounds for future work), in moderate joint positions, influences of individual shoulder anatomy, defects of the articular surfaces, muscle dysfunction, or prostheses can already be systematically and quantitatively investigated using this model.

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