A simplified technique to estimate rotator cuff elongation during complex shoulder motion

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Purpose

Following a rotator cuff injury or surgery, a rehabilitation protocol is usually performed to strengthen shoulder muscles which can be achieved by a wide range of different exercises and several types of technique. Recommendations for design of a shoulder strength training protocol aim at minimizing stress on the rotator cuff by limiting excessive tendon elongation during exercise. Unfortunately, very limited objective data is at disposal to emit such recommendations.

Simulating muscle deformation during motion and thus measuring elongation in-vivo are challenging. Current physically-based methods (e.g., finite element models) are difficult to set up and limited to simple shoulder motion simulation where loads can be estimated [1]. Moreover, they require accurate muscles segmentation on medical images which remains a complicated task. Other methods have considered the modeling of muscle paths, but to provide valid bone penetration-free deformations, numerous wrapping points or objects must be determined for each muscle segment at various joint positions [2], which becomes even more intricate when simulating the shoulder joint during complex motion such as strengthening exercises.

Our goal was thus to devise a simplified technique to simulate rotator cuff muscles during complex shoulder motion. Our second objective was to study the impact of the most common shoulder rehabilitation exercises on rotator cuff elongation.

Methods

One healthy male volunteer (28 years old) underwent magnetic resonance imaging (MRI) of the shoulder. Images were acquired in supine and neutral shoulder position, as well as in six specific shoulder positions: 30°, 60° and 90° of abduction, 90° of abduction with maximal external rotation, 90° of abduction with maximal internal rotation, and maximal flexion. Using the images in neutral position, patient-specific 3D models of the shoulder bones were reconstructed using Mimics software (Materialise NV, Leuven, Belgium). The rotator cuff muscles (infraspinatus, supraspinatus, teres minor, and the superior/inferior bundles of the subscapularis) were also modeled using 3D splines. Attachment sites and trajectories were identified on the MR images.

Kinematic data from the volunteer was recorded using optical motion capture during 31 rehabilitation exercises targeting 11 most frequently trained shoulder muscles or muscle groups and using up to four different techniques when available: cable bar machine, dumbbell, body weight and TheraBand™. Glenohumeral kinematics was computed from the markers trajectories using a validated biomechanical model [3] which accounted for skin motion artifacts. The model was based on a patient-specific kinematic chain using the shoulder 3D models reconstructed from MRI data and a global optimization algorithm with loose constraints on joint translations (accuracy: translational error <3mm, rotational error <4°). As a result, the subject's shoulder 3D models could be visualized at each point of the movement (Fig. 1).

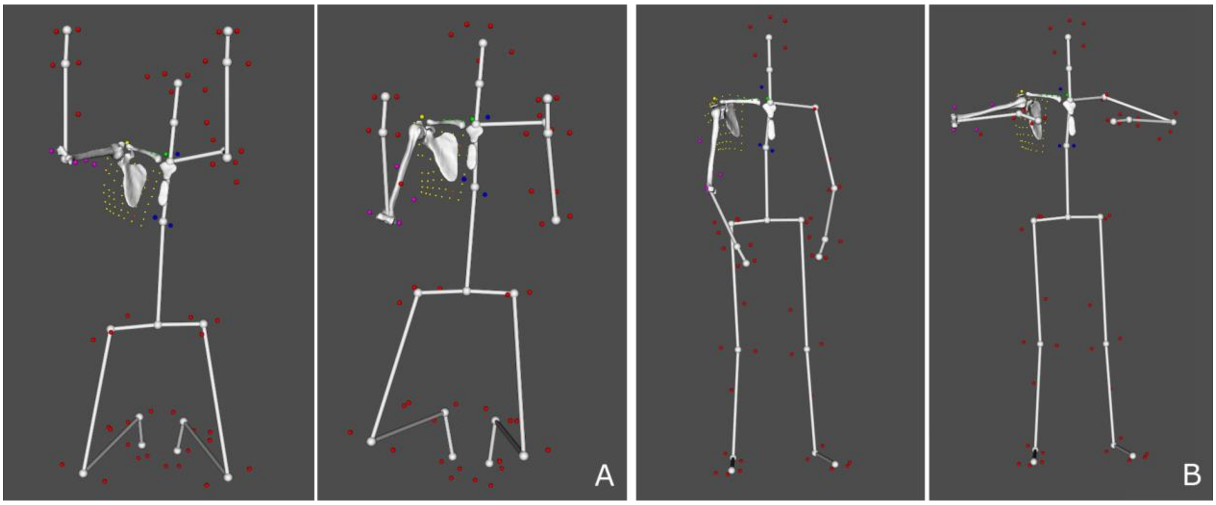

Fig. 1: Examples of computed postures (here the right shoulder) showing the markers set-up (small spheres) and a virtual skeleton used to better visualize and analyze the motion as a whole: A) chin-up exercise (start/end positions) and B) cable upright row exercise (start/end positions).

During motion, muscles were simulated using a position-based dynamics approach [4]. The splines were discretized into a set of connected particles. In contrast to common dynamic simulation models – which rely on the calculation of forces to determine accelerations, velocities and ultimately particle positions using numerical integration methods – position-based dynamics directly derive position updates from the particle positions itself using constraints. The primary constraint used in our simulation is a straight-forward distance constraint which attempts to keep the distance between two particles equal to a specified rest-length. All constraints are processed one by one in a Gauss-Seidel type manner. To prevent interpenetration between the 3D bone models and the splines, continuous collision detection was used [5]. Collision constraints were generated and added to the simulation, moving potentially penetrating particles back to the surface of the 3D bone model.

A validation was performed by comparing the muscles lengths computed by the simulation with those measured on the MR images in the six specific shoulder positions. This was achieved by registering the 3D bone models to each MRI pose in order to retrieve their exact position and orientation to be used as input in the simulation. Reference lengths were obtained by reconstructing the muscles paths for each MRI pose.

The proposed technique was then used to compute maximal muscles lengths on the entire range of motion during the rehabilitation exercises. For clarity, the obtained measures were expressed as muscle length variation (ratio of current length with respect to the neutral position in %). Moreover, a color scale was used to visualize the length variations of the 3D splines, with warm colors denoting elongation and cool colors indicating compression (Fig. 2).

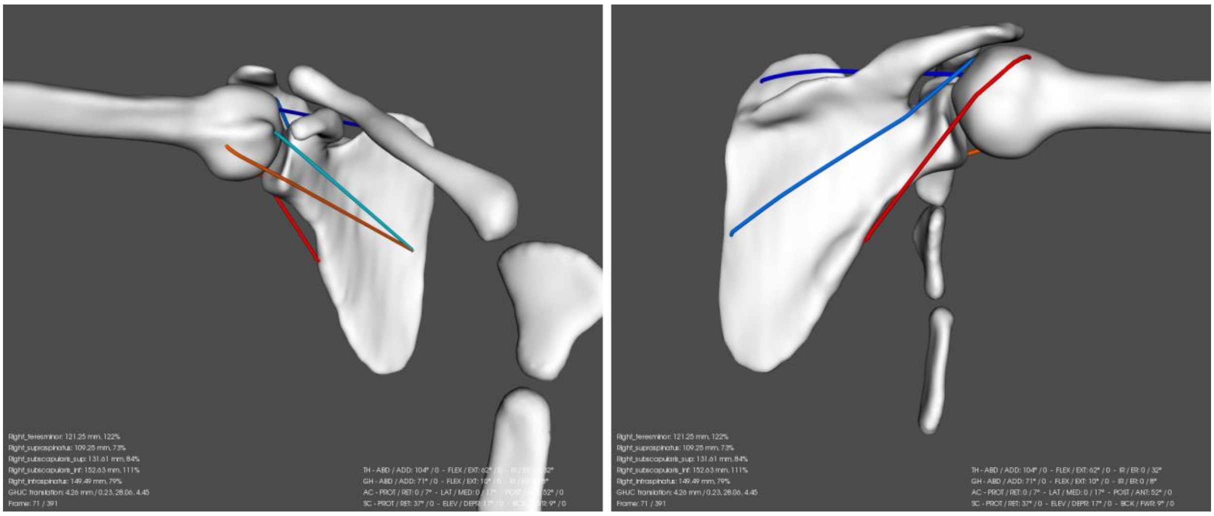

Fig. 2: Rotator cuff muscles simulation during the cable incline shoulder raise exercise (front and back views). The colors represent the length variations with respect to the neutral position: warm colors mean that the muscle is elongated, whereas cool colors mean that the muscle is compressed during motion.

Results

Muscle lengths computed by the simulation showed good agreement with respect to MRI measurements in the different positions, but were always underestimated due to the nature of the simulation technique. The simulated teres minor and subscapularis muscles presented small length errors (mean ± SD: -0.5 ± 0.1 mm and -0.9 ± 0.6 mm, respectively), while the infraspinatus and supraspinatus muscle lengths were slightly more underestimated by the simulation (mean ± SD: -8.6 ± 4.6 mm and -3.6 ± 2.3 mm, respectively).

Maximal muscle length variations ranged between 81% and 138% for targeted muscles exercises according to the training technique used. The teres minor and the inferior bundle of the subscapularis were the most solicited. Least favorable target muscles training with respect to rotator cuff elongation were deltoid, pectoralis major and serratus.

Conclusions

We presented in this study a muscle simulation technique based on a patient-specific bone-muscle representation enabling a stable and real-time simulation of the rotator cuff during complex shoulder motion. Although the proposed technique is a simplified non-physical approach, it allows gathering valuable clinical data. In particular, it offers novel insights into the analysis of the rotator cuff deformation and elongation during functional movements that could be, with further studies, generalized to other muscles or soft tissues (e.g., ligaments).

To our knowledge, this study represents the first screening of shoulder strengthening exercises to identify potential deleterious effects on the rotator cuff. These results, combined with those from our previous work which aimed at assessing cartilages compression and subacromial space variations during the same exercises, will provide useful recommendations to clinicians when restoring patient’s mobility and strength.

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