INTRODUCTION:
Rotator cuff tears are a common cause of shoulder pain and dysfunction. Surgical repair attempts to restore the normal anatomic relationship of the rotator cuff tendons as well as glenohumeral motion. However, rotator cuff re-tear rates are reported as high as 90% with most studies demonstrating rates from 25% to 35%. Despite several reports detailing the potential causes for re-tear which includes anchor and fixation strength, suture materials, suture pulling through tendon, how these re-tears occur in vivo is not known.

Rehabilitation after rotator cuff repair consists of motion and strengthening using several modalities including elastic resistive devices, the success of which, may affect clinical outcomes. While many of these exercises have been well described, little is known regarding the actual forces sustained across the glenohumeral joint or sustained by a repair construct in vivo during these exercises.

A number of experimental studies have investigated the contributions of the individual shoulder muscles to glenohumeral joint stability during various motions of the upper limb. An important limitation of the in vitro studies is that the loading applied to the cadavers are substantially different from that which is present in vivo. The magnitudes of the muscle forces applied in these experiments were also well below the values estimated from mathematical models.

In the present study, we used a computational model of the upper limb to determine individual muscles forces as well as the contributions of the individual shoulder muscles to glenohumeral joint loading during the forward punch rehabilitation exercise. The specific aim was to determine glenohumeral joint reaction forces as well as the relative contributions of the rotator cuff muscles to glenohumeral joint load over the range of motion during this exercise.

METHODS:
A 3D computer model of the upper limb was used to calculate muscle and joint-contact loading at the shoulder during the forward punch exercise. The model and its construction has been described previously. In brief, eighteen muscle bundles were used to represent the lines of action of 11 muscle groups spanning the glenohumeral joint. The path of each muscle bundle was calculated using the obstacle-set method described by Garner and Pandy (2001). 3D bone positions measured in one healthy young male subject who volunteered and signed informed consent (age, 34 yrs; height, 179 cm; weight, 81 kg) performing the Forward Punch exercise were used as input to the model. Steinman pins were inserted into the clavicle, scapula, and humerus, and the three-dimensional coordinates of markers mounted on the pins were recorded (120 Hz) using a 10-camera motion capture system (Motion Analysis Corp., Montview, CA). The relative positions of the bones were measured from 45-90° of humeral forward flexion with an external load applied by an elastic band.

An optimization problem was solved to calculate the forces developed by the shoulder muscles for each prescribed position of the model arm during the forward punch. The problem was to minimize the sum of the squares of all muscle stresses subject to two constraints: (1) that the arm remains in static equilibrium at each described angle of humeral abduction; and (2) that the line of action of the resultant force acting between the humeral head and the glenoid remains within the glenoid cavity. The force of the elastic band was applied to the model hand. The optimization solution was used to determine each muscle’s contribution to glenohumeral joint loading during the motion. Specifically, each muscle force vector was resolved into three components: an anterior-posterior shear force, a superior-inferior shear force, and a compressive force.

RESULTS:
The middle deltoid produced the largest force during the motion (415 N). Of the cuff muscles, the infraspinatus produced a peak force of 235 N at 75° and the teres minor produced a peak force of 137 N at 90° of forward flexion. All other cuff muscles forces were negligible (<25 N; Figure 2). Peak resultant glenohumeral joint reaction force was 880 N at 60° and was comprised primarily of the compressive force which exhibited a peak of 873 N at 60° (Figure 3). The largest posterior shear (-169 N) and inferior shear (-134 N) forces occurred at 45°; and the largest anterior (171 N) and superior shear (174 N) GH loads occurred at 90° of forward flexion.

DISCUSSION:
This study estimated shoulder muscle forces during a common rehabilitation exercise with a 3D computational model validated in previously published works. Maximal infraspinatus muscle forces were recorded as high as 235 N during the Forward Punch exercise. Reported pull out strengths of various shoulder suture anchors have ranged from 112-371 N. The results of this study illustrate the exceptionally high tensile forces that may occur at the infraspinatus tearing or even potentially exceeding the repair construct load to failure. Thus, the results of this study warrant caution to be employed during the rehabilitation phase of rotator cuff repairs and may bring into question the utility of commonly employed exercises.

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