Preliminary Biomechanical Analysis of Superior Capsular Reconstruction Grafts During Activities of Daily Living

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Introduction

Rotator cuff tears are painful and often debilitating injuries that are especially prevalent in older adults[1]. While many cuff tears can be surgically repaired, massive 'irreparable' tears present a special challenge for patients and shoulder surgeons alike. Recently, a superior capsular reconstruction (SCR) technique has been developed to address this problem, which utilizes a dermal allograft spanning the superior region of the glenohumeral joint that inserts into the glenoid rim and the greater tuberosity of the humerus. While SCR does not restore the cuff, the graft reinforces the superior capsule—thereby providing leverage and support to the proximal humerus that is normally provided by cuff tendons[2]. Preliminary studies indicate that SCR is effective in improving shoulder function[2,3]; however, the biomechanical limitations of this repair technique have yet to be sufficiently explored.

The goal of this study was to identify physical activities that may overburden the implanted graft and cause premature failure. To achieve this task, results from an in vitro experiment and an in vivo 3-D motion tracking session were used as inputs for the development of a musculoskeletal model (Fig 1).

Materials and Methods

A single cadaveric upper extremity (female, 96 years old) was used in this experiment. The specimen was skeletonized such that all muscle, tendon, and capsule tissues surrounding the shoulder joint were removed. The SCR repair was performed by an experienced surgeon using a single-row suturing technique. The scapula was secured to a test frame (TA ElectroForce 3550) and the potted humerus was secured to the actuator in the anatomic position. The humerus was driven superiorly at a rate of 0.5 mm/s until failure of the graft occurred.

Upper extremity kinematics during activities of daily living were captured using motion analysis on a young male (22 years old). Reflective markers were adhered the xyphoid process, sternum, C7 vertebra, right acromion, medial and lateral condyles of the elbow, radius and ulna of the wrist, and back of the hand. The subject performed six activities of daily living: combing his hair, a forward reach, an overhead reach, tucking the back of his shirt, washing his back, and washing his opposite shoulder. Marker traces were used to inform the computational model of upper extremity motions in 3-D space.

The musculoskeletal model of an SCR shoulder was developed in OpenSim and was based on a previously published upper extremity model[4]. The model consisted of six segments (thorax, clavicle, scapula, humerus, forearm, hand) and had 13 degrees of freedom. No active muscles were included, as this study was purely a kinematic assessment of glenohumeral motions to make estimations of strain and loads imparted onto the SCR graft.

The graft was modeled with four parallel ligament elements that were attached on the rim of the glenoid and the greater tuberosity to mimic the cadaveric insertion points. A wrapping sphere was used to represent the humeral head. Ligament resting lengths were based on fiber lengths when the shoulder was in the anatomic position. A simple simulation consisting of prescribed superior translation of the humerus at a rate of 0.5 mm/s was performed to mimic the in vitro experiment. Physiological cross sectional area forces and normalized force-length curves were adjusted to reproduce the force displacement data that was measured experimentally.

Joint kinematics were calculated using the OpenSim inverse kinematics tool to track in vivo data collected using motion analysis. Individual ligament forces and lengths, as well as average fiber lengths and total graft forces were quantified for each motion.

Results

Activities involving ligament-lengthening posterior shoulder rotation (back washing and shirt tucking) excessively loaded the graft, which may cause graft failure. Throughout these motions the average fiber length exceeded the experimentally determined ultimate strain (dashed line, Fig. 2A). Simulated graft failure is shown as sharp decreases of total force near 180N (Fig. 2B). These values are slightly lower than the experimentally measured ultimate force of 216N. This is explained by the fact that individual fiber lengths differed during motions, causing some fibers to reach ultimate strains and "break" while others remained intact. Fibers did

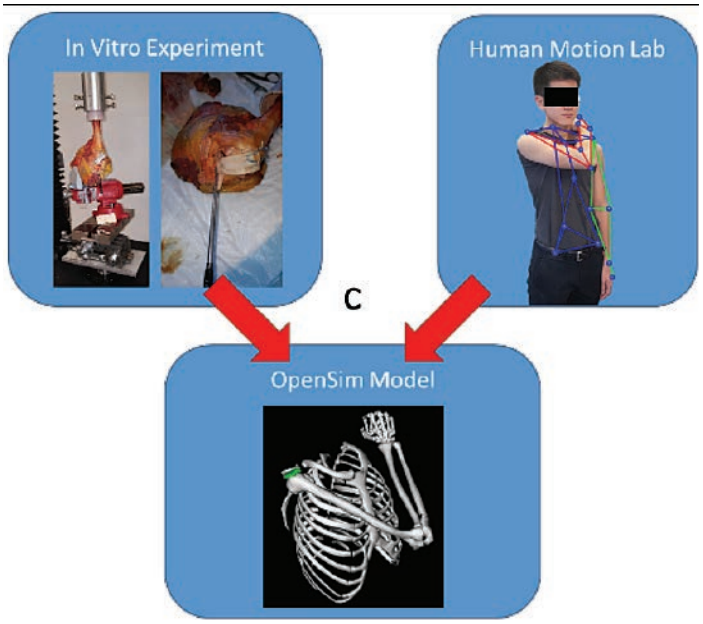

Figure 1. Mechanical properties of the grafts were characterized with an in vitro experiment, while activities of daily living were recorded in 3-D. Both experiments provided input to the OpenSim model.

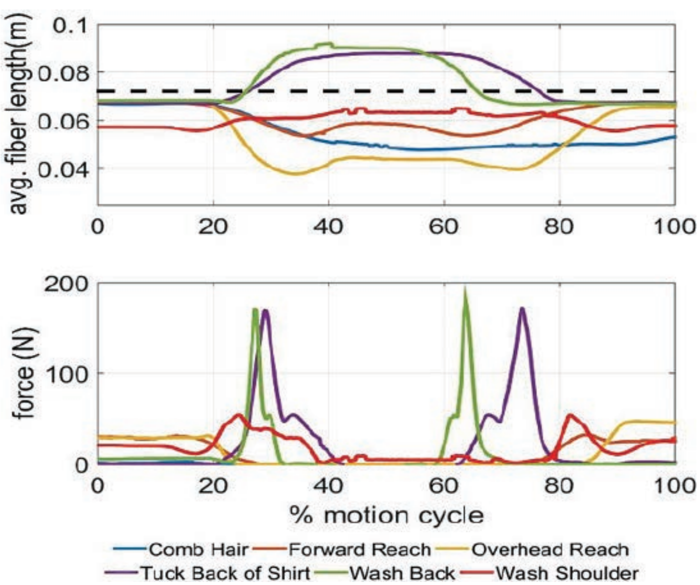

Figure 2. (A) Average fiber length and **(B)** total force exerted on SCR fibers throughout activities of daily living.

not exceed their failure points during hair combing, forward reaching, overhead reaching, or shoulder washing motions.

Discussion

While SCR has shown promise as a repair strategy for massive irreparable rotator cuff tears, the biomechanical limitations of the grafts are still not well-defined. This model identified post-surgical activity limitations that may better inform surgical outcome expectations. These preliminary results also demonstrate the capacity of coupling in vitro, in vivo, and in silico modeling techniques in one cohesive experiment. This approach has potential to provide valuable information to clinicians and rehabilitative specialists to manage patient expectations and guide rehabilitation.

This study was preliminary in nature and has several limitations. While the results suggest that this model is capable of identifying high-risk activities, the small sample size precludes our ability to make strong conclusions about its efficacy. Additionally, the modeling could be improved by including muscle forces and articular joint contact, so that the influence of internal and external loads on the shoulder joint could be assessed. Finally, failure of the in vitro graft occurred at the glenoid insertion, so graft failure biomechanics could be improved with stronger fixation (i.e. double-row suture techniques).

More work is needed to explore the full implications of this preliminary study. In future experiments, we intend to repeat cadaveric simulations, assign validated biomechanical properties to our model ligaments, and validate the model with motion capture data collected in patients treated with SCR.

Acknowledgement

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