Computational Optimization of Graft Tension in Simulated Superior Capsule Reconstructions

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Introduction

Superior capsular reconstruction (SCR) has received increased attention as a surgical technique to address massive 'irreparable' rotator cuff tears, however, the graft loading mechanics during activities of daily living remain poorly understood. In addition, very little is known about the influence of initial graft positioning and tensioning with regard to implant performance and longevity. The goal of this study was to characterize the biomechanics of this repair by: 1) identifying activities of daily living that may overburden the graft, and 2) optimizing the graft placement used during implantation.

Methods

In Vitro Cadaveric Experiment

Six skeletonized cadaveric upper extremities from 5 donors (4M, 1F, mean 65.6 y.o) were used in this study. An SCR repair with a dermal graft (Allopatch HD, Arthrex, Naples Florida) was performed on by an experienced orthopaedic surgeon. Specimens were 3-D scanned (Einscan, Afinia, Chanhassen, MN), fitted with reflective markers for motion capture (Optitrack, Natural Point Inc., Corvallis, OR), and securely mounted to a universal test frame (TA Instruments 3550, New Castle, DE). A load to failure protocol was performed by translating the humerus superiorly (relative to the stationary scapula) at a rate of 0.5 mm/s[1] until rupture of graft fixation occurred at the anchor points on the glenoid. The 3D geometry and motion data were used to create 6 degree-of-freedom simulations of the experiment in OpenSim[2] and to calculate the 95% confidence interval of the ultimate graft strain before failure was calculated.

In Vivo Motion Analysis

With institutional review board approval, upper extremity kinematics of nine different ADLs (Table 1) were captured using motion analysis (Raptor Series, Motion Analysis Corp, Santa Rosa, CA) on eight subjects (4M, 4F, mean age 21.5 ± 1.4 y.o). Shoulder kinematics were calculated for each subject and then 95% confidence intervals for the three glenohumeral joint angles were calculated for each ADL.

Table 1. Activities of Daily Living Performed

1. Reach behind head
2. Comb hair behind head
3. Lift heavy object overhead
4. Lift heavy object to shoulder height
5. Lift light object overhead
6. Lift light object to shoulder height
7. Tuck in shirt behind back
8. Wash middle back
9. Wash opposite shoulder

In Silico Musculoskeletal Modeling

A validated OpenSim model of the upper extremity[3] was modified to include a virtual SCR repair (Figure 1A).The kinematic envelopes of glenohumeral motion were explored with simulations of the ADL motions captured with 3-D marker tracking. Maximum graft strains during these simulations were calculated and compared to the experimentally determined failure thresholds previously determined in the in vitro cadaveric experiment. A "safe" zone of operation was defined with as a lower bound of -5% strain and an upper bound of 14% strain, which was based on the 95% confidence interval for failure that was previously determined. Surgical techniques associated with graft tensioning were simulated by iteratively modifying shoulder position, ranging from 0 to 40° abduction, 0 to 40° of forward flexion, and −20° and 20° degrees of internal rotation in 1° increments for a total of 64,000 surgical placements with unique graft tensions.

Results

The cadaveric experiment indicated that the 95% confidence interval for graft ultimate strain was 14.0 – 23.8%. Activities involving ligament-lengthening posterior shoulder rotation (back washing and shirt tucking) were found to excessively strain the graft, which may cause graft failure and require surgical revision (Figure 1B,C). In general, graft elements typically did not exceed their failure strains while lifting objects overhead, lifting objects to shoulder height, hair combing, reaching behind the head, or washing the opposite shoulder. Surgical placement of

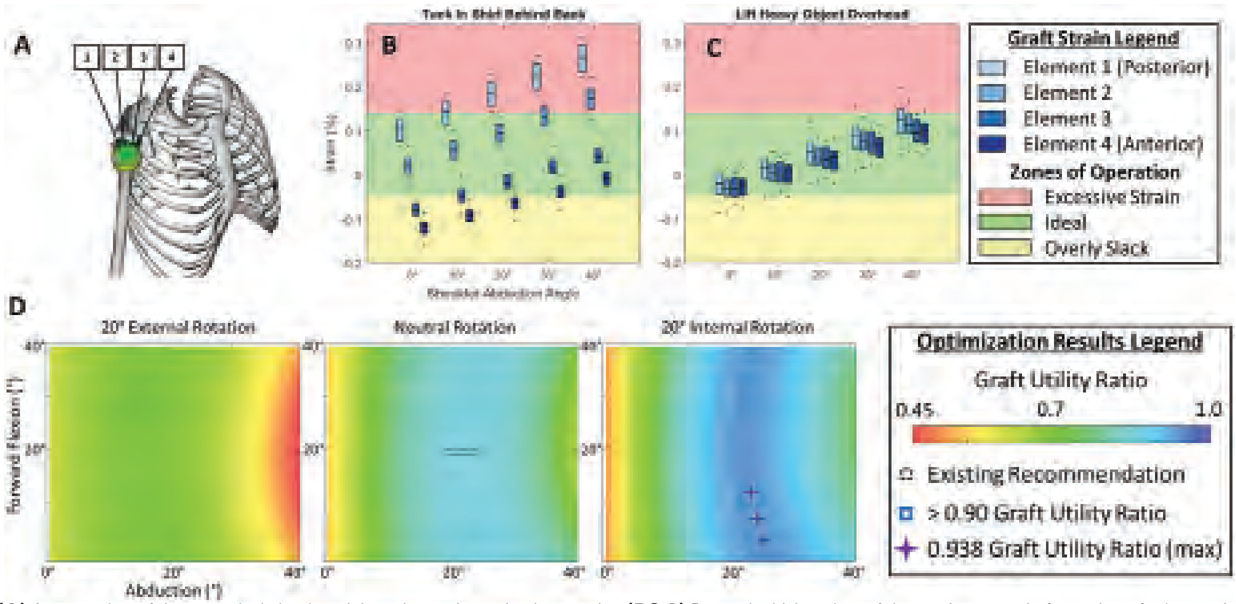

Figure 1: **(A)** A screenshot of the musculoskeletal model used to estimate implant strain. **(B&C)** Box and whisker plots of the maximum strain for each graft element in the model at four different humeral abduction angles during implantation (forward flexion and internal/external rotation were held constant at 0°). Posterior reaching activities, such as shirt tucking, induce a wide spectrum of strain across the length of the graft, and often lead to excessive strain or laxity. **(D)** Results of the optimization presented as heat maps for graft tensioning at three different internal/external rotations. Technique guides currently suggest that the arm should be placed in 20-25° abduction and 20° forward flexion (dashed box), but the results of the current study suggest that orienting the humerus in approximately 25° abduction, and 20° internal rotation during implantation will result in optimal graft performance. Forward flexion angulation does not play an important role in graft strain.

the grafts was sensitive to both humeral internal rotation and abduction (Figure 1C). Humeral orientations of approximately 25° abduction and 20° internal rotation were found to be the optimal pose to hold the arm in during implantation. Placing the humerus in extreme ranges of our test, such as 40° of abduction, and 20° external rotation resulted in scenarios in which excessive strains were applied to the grafts during ADLs. Similarly, poses such as 0° of abduction, and 20° internal rotation resulted in scenarios in which the grafts were consistently slack.

Discussion

This study represents the first biomechanical investigation of the relationships between surgically induced graft tension and simulated post-operative graft performance during ADLs. Activities that involved large amounts of humeral internal rotation tended to excessively strain the most posterior element into ranges associated with graft failure; thus, it is advised that extreme caution should be exercised when performing posterior-reaching activities. Our results indicate that graft utility is optimized by implanting the graft with the shoulder in approximately 25° of abduction and 20° of internal rotation. Previous recommendations, which lack biomechanical validation, suggest placing the shoulder in 20-30° of abduction and 20° of forward flexion[4,5]. While the recommended abduction orientation closely matches the current results, changes in forward flexion angle during implantation minimally affects graft performance. Finally, and perhaps most interestingly, internal/external rotation of the humerus was not included in the previous surgical guidelines. The current results suggest that 20° of internal rotation leads to improved implant performance.

Conclusion

This study implemented a multidisciplinary workflow that utilized *in vitro* biomechanical experimentation, *in vivo* 3-D motion capture, and *in silico* musculoskeletal modeling to identify post-SCR activity limitations and to investigate the relationships between surgically induced graft tension and post-operative graft performance during ADLs. This paradigm presents an additional tool, aside from clinical studies and cadaveric experimentation, to better predict and understand the strengths and limitations of superior capsular reconstruction. More broadly, this approach has potential to be translated to other soft tissue repairs with the goal of providing valuable information to clinicians and rehabilitative specialists to manage patient expectations and guide rehabilitation.

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