The influence of full-thickness supraspinatus tears on abduction moments: the importance of the central tendon

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Abstract

Background: Detachment of the central tendon of the supraspinatus from its insertion is considered to be crucial to functional deficit. The aim of the present study was to assess the function of the supraspinatus in terms of abduction moments by introducing different tear configurations to assess the functional effect of the central tendon insertion.

Methods: Ten fresh frozen shoulders from five cadavers were prepared for testing. A testing protocol was established to measure the abduction moment of the supraspinatus under physiological loading tailored to the anthropometrics of each specimen. Four conditions were tested: intact supraspinatus; complete detachment of portion of the supraspinatus tendon anterior to the main central tendon; detachment of the main central tendon; and detachment of the region of the supraspinatus posterior to the main central tendon.

Results: There was a significant and large reduction in abduction moment when the central tendon was sectioned ($p < 0.05$). A smaller reduction in abduction moment was found when the regions anterior and posterior to the main central tendon were sectioned ($p < 0.05$).

Conclusions: The central tendon is vital in the role of functional arm abduction through force transmission through the intact rotator cuff. Reinsertion of the central tendon in the correct anatomical location is desirable to optimize functional outcome of surgery.

Keywords

biomechanics, *in vitro*, rotator cuff

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Introduction

The central tendon of the supraspinatus is considered to be a vital structure required for force transmission through the muscle to exact arm abduction.^{1,2} The central tendon is akin to a bridge pylon (or tower) that transmits the primary load in a suspension bridge, with the anterior and posterior portions acting as the support cables. The role of the central tendon is currently overlooked in the literature, with the focus being on separating out the anterior and posterior portions.^{3,4} The footprint of the supraspinatus from cadaveric dissection shows a definitive insertional area of the central tendon on the greater tuberosity.^{3,5} There is also a more widespread tendinous insertion over the rest of the

footprint representing the anterior and posterior portion of the supraspinatus.^{6,7} Creating an abduction moment is a key function of the rotator cuff muscles and it is therefore appropriate to test this function when assessing the biomechanical consequences of rotator

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cuff tears.^{8,9} Previous biomechanical testing has loaded cuff muscles according to physiological cross sectional areas from the literature; however, these did not take into account different biometric parameters of individual specimens.^{10,11} Loading can be scaled according to biometric parameters to account for size differences between specimens.

The purpose of the present study is to establish the influence on abduction moments of full-thickness tears with specific reference to tears to the central slip of the supraspinatus tendon. Accordingly, this will test the hypothesis that the central tendon of the supraspinatus is the vital structure for rotator cuff function. To achieve this, a further aim is to develop a new method of testing the biomechanics of *in vitro* rotator cuff tears through a more specimen-specific loading protocol.

Materials and Methods

Ten fresh frozen male shoulder specimens were used from five cadavers, obtained with appropriate donor informed consent (LifeLegacy, Tucson, AZ, USA). Mean age was 59 years (range 45 years to 63 years). The shoulders were disarticulated at the sternoclavicular and scapulothoracic joints. The glenohumeral joint and rotator cuff was therefore removed *en bloc*, intact, with the humerus divided midshaft.

Each shoulder was defrosted and kept moist using physiological normal saline at room temperature for 24 h prior to use. A rotator cuff loading model was used that has been described previously, and was modified to allow the scapula to be secured with an adjustable amount of retraction/protraction, rotation and tilt with the humerus free to rotate.¹⁰ The scapula was mounted at 30° downward rotation so that, when the humeral was vertical, this would correspond to a 30° glenohumeral abduction. The absence of epicondyles in the specimens meant that a reference point for axial rotation could not be taken. Neutral rotation of the humerus was therefore not defined before the loading regimen but was defined after application of equal internal and external rotation moments (Fig. 1).¹²

The overlying soft tissue structures (skin, fat and bursa) of the shoulder were excised to reveal the underlying rotator cuff tendons. The clavicle was removed to expose the supraspinatus. The rotator cuff tendons were still attached to their origin and insertions. The anterior, posterior edges and the central tendon of the supraspinatus were identified and marked out. An absence of rotator cuff pathology in every shoulder was confirmed visibly by dissection and inspection on the superior surfaces of the tendons prior to testing and on the inferior surfaces after testing. Each rotator cuff muscle was then carefully dissected from their medial origins. The medial ends of the muscle bellies were

secured with household flannel and 2 (5 metric) Orthocord (DePuy Synthes, Raynham, MA, USA) with a reverse cutting needle to act as an attachment. The muscle belly was attached to a mass via a pulley system, using electrical wire to secure the medial end and provide substantial grip and prevent pull out of the suture. Pulleys attached to the rig allowed the horizontal and vertical alignment to be in the direction of pull of the tendon.

An intramedullary rod was inserted retrograde into the medullary canal of the humerus 10 cm below the level of the supraspinatus insertion. Attachment of counter weights to the rod via a pulley system allowed balancing of the abduction moment produced by the loading on the rotator cuff muscles, keeping the humerus vertically aligned. A spirit level was also used as a reference marker to ensure verticality of the intramedullary rod. The supraspinatus, subscapularis, infraspinatus and teres minor were then loaded in a specimen-specific manner as described below.

The UK National Shoulder Model (UKNSM) was used to quantify muscular contraction forces for a static 30° humerothoracic abduction, achieved in testing by adjusting the scapula, therefore allowing the humerus to be mounted vertically.^{13–15} The segment lengths and muscle insertions were scaled according to the height of the specimen donor relative to the height prescribed in the Visible Human Dataset.¹⁶ This method of scaling was used, because the bony landmarks of the thorax, clavicle, humerus and forearm were not supplied by the tissue bank. Body segment parameters were scaled with the mass of the donor according to the data of deLeva,^{17,18} based on a large group of young living subjects. The calculated muscle forces provided more individually tailored weights for the supraspinatus, infraspinatus, teres minor and subscapularis than in previous literature. These weights were then applied to the appropriate muscle bellies.

The humerus was then loaded to provide a counter balance to the resultant abducting moment and fine adjustments were made to the load on the infraspinatus to maintain a constant position of the humerus preventing rotations around the glenohumeral joint. This ensured that the start point for every test was identical. The testing rig then stood for up to 10 min, so that there was no change in the humerus position as a result of creep.

Two sectioning protocols were followed, both producing full-thickness tears in different sequences, resulting in four conditions: intact supraspinatus; complete detachment of the portion of the supraspinatus tendon anterior to the main central tendon; detachment of the main central tendon; and detachment of the region of the supraspinatus posterior to the main central tendon (Fig. 2). All tears were created from the bursal side.

Figure 1. The test rig set up with mounted shoulder (posterior view).

Figure 2. The humeral head from above: insertion site of the supraspinatus (interrupted green line) and articular cartilage of the humeral head. The central tendon is shown with a blue nylon suture.

The anterior, posterior and central tendon portions were separately identified macroscopically and marked out. A previously custom designed template was used to ensure that a standardized and repeatable rotator cuff tear/defect could be created at the supraspinatus insertion.¹¹ The template was made from stainless steel and shaped into a semi-circle with a width of 20 mm and maximal depth of 5 mm. The device allowed accurate repeatable placement of the template onto the superior surface of the supraspinatus tendon. Once the template was positioned on the supraspinatus tendon, a 15 carbon steel surgical blade was used within the confines of the template to produce a full-thickness tear according to the protocol being assessed.

The tendon was cut in 5-mm increments and at each stage the counter balance required to act on the humerus was applied and recorded. The tear was completed according to the protocol until the whole supraspinatus was detached from the humerus.

In Protocol 1, first, a full-thickness tear was produced, starting at the posterior edge of the supraspinatus, then through the central tendon and, finally, incorporating the anterior edge of the tendon until the supraspinatus was completely detached from its insertion. Protocol 2 started with detaching the central tendon, then the anterior portion, followed by the posterior portion. The two different sequences were selected to enable independent comparison of the sectioning of each individual portion. The central tendon was found by physical inspection. At each stage, the loads applied to the muscles and the counter balance required to act on the humerus was applied and recorded. Shoulder specimens were paired so that one donor provided a specimen to each protocol.

Data were tested for normality using the Shapiro–Wilk test. Where normality was preserved, paired *t*-tests were used to compare conditions. Friedman nonparametric tests, with Wilcoxon signed ranks *post hoc* tests, were used in all other cases, with a Bonferroni correction.

Data were analyzed to test for differences between the first and last loading conditions in the two protocols (fully intact, fully sectioned). Data were analyzed to test for differences between all three states of incision in a pairwise manner.

All statistical analyses were conducted using SPSS, version 21.0 (IBM Corp., Armonk, NY, USA).

Results

The anthropometrics of the cadavers used for testing and the specific loads determined by the UKNSM are

shown in Table 1. All subjects were male. The balancing forces are shown in Table 2. There was no statistical difference between the two groups at the start of testing with regards to the loading values and with an intact supraspinatus ($p=0.338$). Similarly, there was no statistical difference between the final balancing force between the two groups ($p=0.099$). This is expected given that the two groups contain shoulders from the same cadavers.

The percentage change in the forces required to balance the shoulder as the sectioning of the supraspinatus occurred are shown in Table 3. These were combined according to the cut made (Table 4), demonstrating that the central tendon contributes 45% of the abduction moment (Fig. 3). The difference in the effect of the section performed was significant ($p=0.05$). A pairwise comparison of the sections then revealed that the detachment of the main central tendon had a greater effect than the posterior and anterior regions ($p=0.05$). No significant differences were found between a posterior and anterior region section. This shows that the sectioning of the main central tendon is the most significant change to the moment producing capacity of supraspinatus in this loading condition.

Discussion

Rotator cuff tears are a common condition. Symptomatic tears involve pain and loss of function.¹⁹ Pain may be managed without reconstruction of the rotator cuff through medication, corticosteroid injection, physiotherapy, debridement and subacromial decompression, with good outcomes widely reported.²⁰ Reconstruction of the rotator cuff is a significant undertaking.²¹

The present cadaveric study shows that the majority of changes to the supraspinatus abduction moment

Table 1. Cadaver anthropometrics and UKNSM determined loading of supraspinatus (SS), infraspinatus and teres minor (IS/TM), subscapularis (SBS) and humeral counter balance (HCB).

Anthropometrics					Tendon loads (N)			
Cadaver	Age (years)	Body Mass (kg)	Height (m)	BMI	SS	IS/TM	Sub	HCB
1	61	74	1.60	29	52	10	10	15
2	65	70	1.75	23	47	25	16	10
3	46	67	1.78	21	46	14	15	10
4	61	77	1.78	24	53	30	18	15
5	63	91	1.78	29	62	35	21	30

BMI, body mass index.

Table 2. Balancing forces (N) applied for all specimens.

Protocol 1	Specimen	A	B	C	D	E	Mean (SD)
Condition	Intact	15.0	10.0	10.0	15.0	30.0	16.0 (8.2)
	Posterior section	11.5	8.5	9.5	10.0	26.0	13.1 (7.3)
	Posterior plus Central section	7.5	3.0	4.5	4.0	13.0	6.4 (4.1)
	Posterior plus Central plus Anterior section	4.0	1.0	3.5	3.0	7.0	3.7 (2.2)
Protocol 2	Specimen	A	B	C	D	E	Mean (SD)
Condition	Intact	15.0	10.0	20.0	10.0	45.0	20.0 (14.6)
	Central section	10.0	4.0	12.0	7.0	15.0	9.6 (4.3)
	Central plus Anterior section	8.5	2.2	8.0	5.0	12.0	7.1 (3.7)
	Central plus Anterior plus Posterior section	3.0	1.0	3.0	2.5	7.0	3.3 (2.2)

Table 3. Change in balancing force from previous condition of section as a percentage of intact balancing force.

Protocol 1	Specimen	A	B	C	D	E	Mean (SD)
Condition	Posterior section	23.3	15.0	5.0	33.3	13.3	18.0 (10.8)
	Posterior plus Central section	50.0	70.0	55.0	73.3	56.7	61.0 (10.1)
	Posterior plus Central plus Anterior section	73.3	90.0	65.0	80.0	76.7	77.0 (9.2)
Protocol 2	Specimen	A	B	C	D	E	Mean (SD)
Condition	Central section	33.3	60.0	40.0	30.0	66.7	46.0 (16.4)
	Central plus Anterior section	43.3	78.0	60.0	50.0	73.3	60.9 (14.8)
	Central plus Anterior plus Posterior section	80.0	90.0	85.0	75.0	84.4	82.9 (5.7)

occur when the main central tendon is sectioned (Fig. 3). This would reflect the suspension bridge theory that the central tendon is the main pylon and transmits the primary load. Both the anterior and posterior regions contribute to force transmission but to a lesser extent (Tables 2 and 3). The central tendon, when sectioned, allows forces through the remaining portions

to be distributed anteriorly and posteriorly and hence may produce an axial rotation moment on the humerus. This would explain why there is no corresponding higher tension in the remaining attached portions because these parts are merged with the respective anterior and posterior tissues of the remaining cuff; hence, there was no obvious change in the

Table 4. Combined percentage change compared to the intact muscle grouped by sectioned portion.

	Specimen	Posterior	Central	Anterior
Protocol 1	A	23	27	23
	B	15	55	20
	C	5	50	10
	D	33	40	7
	E	13	43	20
Protocol 2	A	37	33	10
	B	12	60	18
	C	25	40	20
	D	25	30	20
	E	11	67	7
	Mean (SD)	20 (10)	45 (13)	15 (6)

Figure 3. Change in balancing force from previous condition of section as a percentage of intact balancing force. The 95% confidence intervals are displayed as error bars. The overall result of a Friedman test looking at the effect of the sections on the balancing force is shown. The results of pairwise comparisons with a Wilcoxon signed ranks test are also shown when significance was found.

**Statistical significance at $p = 0.001$.

tension of the intact segment. However, this did cause an obvious change in the axial rotation moment arm.

We show a specimen specific loading protocol as determined by the UKNSM model. This is the first experiment to do so in a more specimen-specific fashion, tailoring abduction moments and a balanced shoulder to each specific cadaver. Other studies have scaled loading according to the physiological cross-sectional area (PCSA) obtained from the literature, yet none have scaled loading to both the subject and

the specific task/position.¹³ Scaling shoulder model PCSAs has a marginal effect on muscle and joint contact force predictions for submaximal tasks, and was therefore not used.¹³ Geometric model scaling was performed based on height for each subject, which is closely linked to humerus length and thus the key moment arm length at the shoulder during the specific task/position modelled and then used in the present study.²² The availability of ten cadaveric specimens may be a limitation. Biometric data could not be checked as a result of the source of the specimens not providing that information. However, the UKNSM allows a specimen-specific model to be obtained because the tasks are submaximal and the height of the specimens was known.²²

The fundamental aim of repair of the rotator cuff is to improve load transmission and, consequently, strength restoration. The present study demonstrates, *in vitro*, the crucial role of the central tendon in load transmission. The results of the present study show that the single most important structure for consideration of anatomical restoration at the time of surgery is the central tendon and, as such, this lends support to the argument from the literature that *in vitro* restoration of the central tendon is vital to achieving an optimal functional outcome of rotator cuff recovery of strength.²³ Restoration of the supraspinatus central tendon will afford a better chance of restoring the footprint and tension to the repair, as well as decreasing associated pathological changes, such as fatty infiltration.^{5,24}

The results of the present study show that there is a loss of supraspinatus function when any part of the muscle is detached from its insertion. The integrity of the muscle is most significantly related to the degree of the main central tendon involvement with the tear (Fig. 2). When the central tendon is cut, there is a substantial loss of abduction moment. The greatest change in this moment was measured with central tendon detachment, irrespective of the order in which the supraspinatus was released.

Declaration of Conflicting Interests

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Ethical Review and Patient Consent

This study was approved by the Imperial College Research Ethics Committee.

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