Knee Surg Sports Traumatol Arthrosc
(2003) 11 : 389–392

SHOULDER

DOI 10.1007/s00167-003-0404-5

E. J. Nightingale
C. P. Allen
D. H. Sonnabend
J. Goldberg
W. R. Walsh

Mechanical properties of the rotator cuff: response to cyclic loading at varying abduction angles

Received: 20 January 2003
Accepted: 9 April 2003
Published online: 29 July 2003

E. J. Nightingale · C. P. Allen
D. H. Sonnabend · J. Goldberg
W. R. Walsh (✉)
Orthopaedic Research Laboratories,
Division of Surgery,
Edmund Blacket Building,
Prince of Wales Hospital,
University of New South Wales,
2031 Randwick, Sydney, Australia
Tel.: +61-2-93822657,
Fax: +61-2-93822660,
e-mail: W.Walsh@unsw.edu.au

Abstract The rotator cuff is loaded under static as well as dynamic conditions. Whilst the static properties of the rotator cuff muscle-tendon junctions have been reported, the dynamic mechanical behaviour has not. This study reports the dynamic mechanical properties with varying abduction angles in a human cadaver rotator cuff. No significant effect was found with varying the angle of testing or in the presence of a tear in the tendon. The supraspinatus was found to be the stiffest of the rotator cuff tendons followed by the subscapularis and infraspinatus.

Keywords Rotator cuff · Mechanical testing · Abduction

Introduction

The supraspinatus, infraspinatus, subscapularis and teres minor tendons are important stabilisers of the glenohumeral joint [13, 15] involved in abduction and rotation. In vivo, these tendons are subjected to a variety of static as well as dynamic forces as the position of the arm changes during glenohumeral motion. Joint reaction forces at the glenohumeral joint are significantly affected by the integrity of the rotator cuff [15]. The static properties of the intact supraspinatus and its repair have been extensively reported [4, 8, 9, 11, 18]. The mechanical properties of tendons and ligaments have traditionally been examined following quasi-static tensile testing protocols reporting the structural (load and displacement) or material properties (stress and strain) of the tissues. Hadler and co-workers examined the static properties of the subunits of the infraspinatus tendon and teres minor versus joint position [10]. Differences were noted within the different subunits, whilst position of the arm did not affect the ultimate load, stress or stiffness in static testing [10]. Bey and co-workers recently reported the deformation of the rotator cuff as an intact, functional unit using a novel, MRI-based technique to quantify intratendinous strains versus glenohumeral abduction in the scapular plane. The intratendinous strain increased with increasing joint angle and suggested that the joint position may play a larger role in rotator cuff mechanics [3].

Little attention however, has focused on the cyclical behaviour of the tendons of the rotator cuff. Cyclical or dynamic loading may be of particular relevance considering the rehabilitation protocols as well as the repetitive activities of daily living. Rossouw et al. [18] examined the mechanical properties of interosseous sutures and suture anchor fixation using cyclic loading. Repairs loaded cyclically failed at low loads due to suture cutting into bone and tendon, demonstrating the importance of this loading profile. Considering the in vivo loading of the rotator cuff, we hypothesized that the dynamic properties of the rotator cuff tendons may be dependent upon position. This study examined the influence of glenohumeral abduction be-

Table 1 Specimen details

Specimen No.	Sex	Age	Side	Comments
1	F	70	L	Intact
2	M	53	L	Partial bursal side tear
3	M	57	R	Intact
4			L	Partial articular side tear
5	F	81	L	Arthroscopic repair no tendon damage
6	M	69	R	Partial bursal side tear
7	F	81	R	Impingement lesion
8	M	68	R	Partial articular side tear
9	M	68	L	Impingement lesion
10	M	76	R	Intact
11	F	74	L	Full thickness tear
12	M	22	R	Intact
13	F	44	L	Intact
14	M	22	L	Intact
15	M	70	L	Two tears: partial articular and intralaminar
16	M	70	R	Intact
Average	Age	61.7		
Median		69		

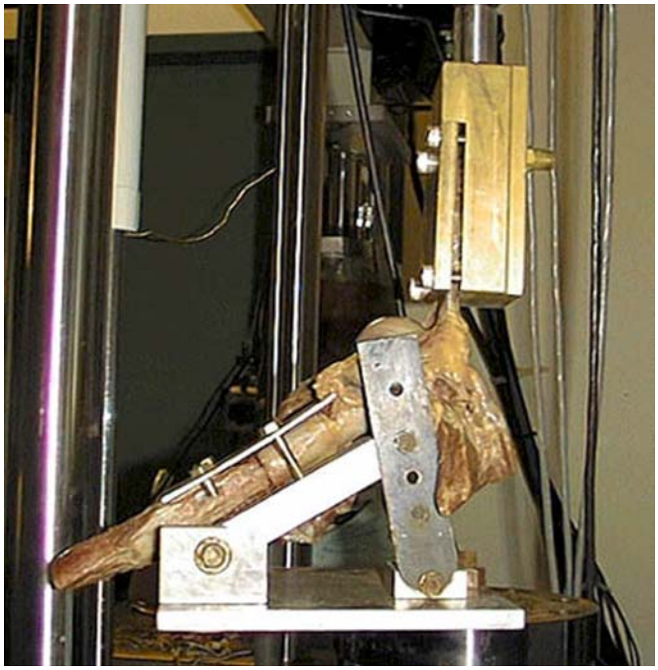

Fig. 1 Test set up demonstrating custom-made jig to alter the abduction angle

tween 10 and 30 degrees on the dynamic properties of the rotator cuff tendons using a human cadaver model.

Materials and methods

Rotator cuff tendons (seven right and nine left shoulders) were harvested from 16 cadaveric specimens aged between 22 and 81 years (median 69 years old) (Table 1). Shoulder specimens were fresh frozen and allowed to thaw for 12–18 h at room temperature prior to dissection. The skin, superficial musculature and clavicle were removed to expose the rotator cuff. The rotator cuff musculature was detached from the scapula and the humeral attachments were left intact. Specimens with tears were included in the study due to the large number of asymptomatic tears in the "normal" older population. The tears were classified as partial or full thickness tears which were present from the bursal to articular aspects of the cuff. The width of the tears prior to mechanical testing was noted. The capsule edge was split to allow free movement of the tendons as individual units. The infraspinatus and teres minor were treated as one functional unit for mechanical testing.

Dynamic tensile testing was performed using an 858 MTS Materials Testing Machine (MTS Systems Corporation, Minneapolis, MN, USA). A custom jig was constructed to fix the humerus stable in neutral rotation and allow glenohumeral abduction to be varied between 10° and 30° (Fig. 1). The muscle belly of the tendon being tested was secured using a freeze clamping method [6, 7, 16] as close to the muscle tendon junction as possible. The muscle belly was frozen using liquid carbon dioxide with care taken not to freeze the tendon itself. Three measurements of the tendon width and thickness were taken along the tendon to obtain an average cross sectional area. Cyclic loading was performed on the supraspinatus, subscapularis, and the infraspinatus/teres minor complex individually as follows: (a) a pre-loading sequence of between 5 N and 50 N for 10 cycles at 0.25 Hz; (b) a holding period of 10 s at 5 N; and (c) a test cycle of between 10 N and 100 N at 0.5 Hz for 10 cycles. Specimens with an existing tear were carefully monitored to determine if the tears progressed during cyclical loading.

The cyclical load and displacement data was analysed by examining the last seven cycles of the test sequence using Matlab. A Fourier series analysis was performed to calculate the dynamic, storage, and loss moduli as well as phase lag. The dynamic modulus (E) is related to the storage (E_s) and loss (E_l) moduli by the equation:

$$E = E_s \sin \omega t + E_l \cos \omega t + \text{constant}$$

Due to this direct relationship between the moduli only the results of the dynamic modulus have been given as representative of the tendon's properties. An analysis of variance (ANOVA) was performed (Statistica, Statsoft, Tulsa, OK, USA) to examine the effect of the tendon (Supraspinatus, Subscapularis, Infraspinatus-teres minor) angle (10–30°), age and presence of a tear (full or partial thickness).

Results

Dissection of the samples for revealed one full thickness and five partial thickness supraspinatus tears that spanned no more than 1 cm in width. The subscapularis and infraspinatus/teres tendons were intact in all specimens. Cross sectional area data for the tendons is presented in Table 2. The supraspinatus tears did not progress upon mechanical loading in the current study.

The dynamic modulus did not vary with abduction angle between 10° and 30° under the loading conditions examined (Figure 2). The dynamic modulus did however differ between the tendons ($p = 0.02$) with the supraspina-

Table 2 Cross sectional area of the rotator cuff tendons

Cross-sectional area (mm^2)	Range	Mean	Standard deviation
Supraspinatus	64–171	114.36	33.8
Subscapularis	72–202.5	122.98	35.5
Infraspinatus	75.4–330	151.67	66.3

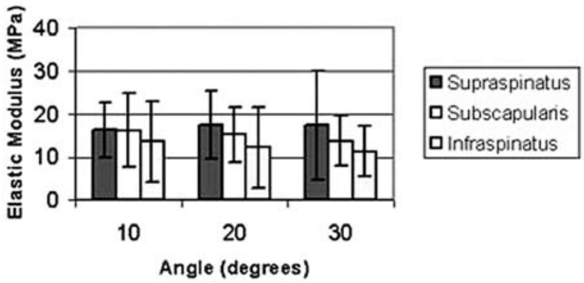

Fig. 2 The dynamic modulus did not vary with abduction angle between 10° and 30° under the loading conditions examined. The dynamic modulus did however differ between the tendons (p= 0.02) with the supraspinatus tendon superior to the others

tus tendon the stiffest (17.3±8.9 MPa) followed by the subscapularis tendon (15.2±6.9 MPa) and the infraspinatus/ teres minor complex. (12.4±8.2 MPa). Specimen age had a significant effect on the dynamic modulus of the supraspinatus tendon only (<60 years of age 21.2 MPa; >60 years of age 15.5 MPa). The presence of a tear in the supraspinatus tendon dynamic did not alter the mechanical properties in the specimens tested.

Discussion

The cryogrip method used has been shown to allow accurate mechanical testing of tendons [6, 7, 14, 16] as well as the bone tendon and musculotendinous junctions [19]. We observed no slippage on testing, and the behaviour of the whole tendon unit was observed. Through testing the whole tendon unit some bone and muscle fibers may have been included, but we attempted to minimize this to prevent inaccuracies in the strain found. The capsule edge was split to allow testing of the individual tendons, but the tendons themselves were not split. This allowed load sharing through the capsule and tendon projections as it occurs in vivo. A pre-cycle loading phase was performed to clear the tissues of their previous strain history [21].

The current study examined the cyclic properties of rotator cuff tendons versus abduction angle in a human cadaver shoulder model. A sub-failure loading regime was used to avoid damage during testing and allow us to test the cuff tendons in each sample. Loading up to 100 N was chosen based on EMG studies of loads ranging from 140–196 N in athletic activities [11]. This loading regime was felt to more closely reflect physiological than failure properties. The abduction angle did not alter the mechanical properties of the tendons in the range tested in the current study. Differences in the properties of the individual tendons were however noted. The presence of a tear in the supraspinatus tendon did not alter the overall gross mechanical properties in the current study. Previous studies have shown that small isolated supraspinatus tears often have minimal effects on glenohumeral motion [1, 20]. On the other hand, Bey and co-workers, using a novel MRI technique, reported that the intratendinous strain fields were influenced significantly by joint position, but few differences existed between tendon regions [2, 3].

The stiffness of the supraspinatus was greater than that of the subscapularis and infraspinatus and teres minor complex. This may be indicative of their differences in internal structure. Fiber direction varies in different tendons [5, 12] and also across regions within the tendon. The articular surface of the supraspinatus tendon has a greater number of collagen fibers in an orthogonal orientation [5]. Riley et al. [17] suggested the supraspinatus has a fibrocartilaginous structure compared to a more tendinous structure for the other cuff tendons. These differences have been linked to variations in the mechanical properties [12]. The effect of age is a more complex problem, and due to the small sample it is not clarified by this work alone. The subscapularis and infraspinatus show no significant change in their mechanical properties with age. Analysing the supraspinatus specimens based on age (above 60 years and less than 60 years old) revealed a trend of decreasing stiffness with age (p=0.06).

Comparing our results to studies using cyclical testing of rotator cuff repairs is difficult due to the different testing methods used [4, 9, 18]. The loads used vary between 100 N and 250 N, with all studies confirming that tendon separation occurs in a short period of time with failure occurring by bone and tendon cutting. Gerber et al. [9] found that the Mason Allen tendon attachment method was the only method to withstand over 1000 cycles at 250 N. Burkhart et al. [4] found that a 10 mm gap occurred at an average of 188 cycles when loaded at 180 N. Rossouw et al. [18] found a permanent deformation occurred after only 20 cycles with a 100 N load. Our results demonstrated rotator cuff tendons (with and without tears) withstand cyclic loads up to 100 N without increases in tear sizes and without damage occurring to the tissues. This suggests that repairs are insufficient to withstand normal activities post operatively and that a period of immobilization is required to allow healing to commence before normal activities can be recommenced.

The rotator cuff has been confirmed as well adapted to work throughout a range of 10–30 degrees with no variation in the mechanical properties of the tendons. When coupled with scapular thoracic movement this allows a 0–45° range clinically. This is significant, being the range used most in activities of daily living. The supraspinatus tendon was found to be the stiffest of the rotator cuff tendons under the current testing conditions. Differences in the internal structure of the supraspinatus tendon being more fibrocartilaginous may account, in part, in differences observed in the mechanical properties. Whether the differences in structure between the tendons or differences in loading patterns are the reason for the increased incidence of tears in the supraspinatus is unresolved. Age related changes have also been suggested as playing a role in altering the properties of the supraspinatus, which may lead to the increased incidence of tears in this tendon over the others, but requires further investigation. Finally, this study was limited in that higher degrees of abduction beyond 30° were not examined.

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