This study reports the application of a novel method for quantitatively determining differences in the mechanical properties of healthy and torn rotator cuff tissues. In order to overcome problems of stress risers at the grip-tendon interface that can obscure mechanical measurements of small tendons, we conducted our investigation using dynamic shear analysis.

Rotator cuff tendon specimens were obtained from 100 patients during shoulder surgery. They included 82 differently sized tears and 18 matched controls. We subjected biopsy samples of 3 mm in diameter to oscillatory deformation under compression using dynamic shear analysis. The storage modulus (G') was calculated as an indicator of mechanical integrity.

Normal tendons had a significantly higher storage modulus than torn tendons, indicating that torn tendons are mechanically weaker than normal tendons (p = 0.003). Normal tendons had a significantly higher mean shear modulus than tendons with massive tears (p < 0.01).

Dynamic shear analysis allows the determination of shear mechanical properties of small tissue specimens obtained intra-operatively that could not be studied by conventional methods of tensile testing. These methods could be employed to investigate other musculoskeletal tissues. This pilot study provides some insight into mechanisms that might contribute to the failure of repair surgery, and with future application could help direct the most appropriate treatment for specific rotator cuff tears.

Rotator cuff degeneration and tears affect between 5% and 30% of adults. It is estimated that 40% to 50% of the general population consult their general practitioners for shoulder pain at some stage. The presence of a rotator cuff tear correlates with inferior shoulder function. The intra-articular synovial environment of the damaged tendon can preclude healing, and repair is often required. The failure rates following sutured repair and synthetic or tendon grafts vary between 13% and 68%. Re-rupture is associated with a poor outcome, but there remains an overall improvement in pain compared to pre-operative levels. Larger tears are more difficult to manage owing to the higher associated incidence of re-rupture. Better results in the treatment of massive tears may be obtained following an augmented repair using a polyester ligament.

Evidence using a multistage disease model suggests that the metabolism, cellular and composition of the extracellular matrix of the edge of the torn tendon change significantly as the size of the tear increases. It is yet to be determined whether these changes affect the mechanical properties of the tendon. However, understanding the mechanical properties of the tissue adjacent to a tear may provide insight into the mechanisms underlying the generation of a tear and the failure of some tears to heal after surgery. The purpose of this study was to develop a test of the mechanical properties of small human specimens obtained prospectively at surgery from normal and torn rotator cuff tendons, in order to assess whether there are mechanical differences between different sized tears and normal tendons.

A major problem preventing the tensile mechanical testing of small tendon samples is failure to uniformly and consistently grip specimens. Stress risers at the clamp-tendon interface can obscure or invalidate measurements. Therefore, despite a wide body of literature and an extensive experience of tensile testing, we are unaware of any studies comparing the tensile properties of normal and torn human rotator cuff tendons obtained intra-operatively, owing to the technical difficulties encountered.
order to obtain a comprehensive understanding of rotator cuff mechanics, shear analysis as well as uniaxial tensile testing is important, as these tendons are subjected to multidirectional forces involving shear and compression. They are also structurally inhomogeneous anisotropic materials that show a non-linear response to loading.

In order to overcome the problem of gripping small specimens of human tendon and to avoid clamping artefacts, we developed dynamic shear analysis. This is a novel technique based on rheometry, the study of flow and material deformation of samples in response to shearing mechanical stress. Different materials deform differently in response to such stresses, and this offers insight into their mechanical properties. It will have been observed how a spoonful of mayonnaise spreads easily but leaves an indentation within the jar, whereas a spoonful of honey does not spread as easily but leaves no residual indentation. Viscoelastic behaviour can be quantified in oscillation, and almost all biomaterials, including bone, sit within a viscoelastic spectrum of soft condensed matter and therefore can be tested using dynamic shear analysis. Performing this analysis on tendons allows calculation of the bulk storage modulus\(^\left(G'\right)\); which provides an indicator of mechanical integrity. Thus dynamic shear analysis provides the potential for further investigation, as it could help predict the success of surgery by identifying tears which are likely to propagate or re-rupture. Working from a null hypothesis of no discernible differences, we nevertheless expected that torn rotator cuff tendons would have altered structural and mechanical characteristics compared to normal tendons.

**Materials and Methods**

**Patients and specimen collection.** Biopsies were obtained during open surgical repair of rotator cuff tears in a non-randomised, prospective case-controlled study. Tears were diagnosed pre-operatively with ultrasound. Exclusion criteria included patients who had previously had surgery on their shoulder, connective tissue disorders, osteoarthritis, or rheumatoid arthritis of the shoulder. A total of 82 full-thickness biopsies were taken from the same location at the anterior edge of a chronic rotator cuff tear from 82 patients, with a mean age of 65.2 years (47 to 83). The size of the tear was measured intra-operatively and classified as small, medium, large or massive. 17 Matched controls were obtained from each biopsy and a mean was calculated for each tendon specimen. Assessment of the test retest variability found that the correlation coefficient \(r\) was 0.73 \((p = 0.038)\). The samples were loaded between two parallel plates in an environmental chamber at 37°C and 100% humidity to keep the water content constant. Prior to the study, the criteria for valid modulus readings were set as: a) a thrust of approximately 20 g, and b) an approximately 1 mm gap between the two parallel plates within which the tendon was compressed. Samples were then subjected to a standard oscillatory test \((0.623 \text{ rad/s to 39.6 rad/s, 0.001 strain})\) (Fig. 1). The upper plate moves sinusoidally at a fixed strain and records the stress response from the tendon samples over a range of frequencies \((\omega)\) by measuring the torque on the drive motor. The digitally mapped bearing of this motor is used to record the absolute displacement, which is converted to strain. The resulting strain peak \((\gamma_p)\), stress peak \((\sigma_p)\) and difference in phase \((\delta)\) was measured for each frequency. These values were used to calculate the elastic (storage) modulus \((G')\) (Fig. 1). The mean storage modulus across all frequencies was used to indicate the mechanical integrity of the tendons. The observers (SC, CH) were blinded to the size of the tear from which the samples had been collected.

In order to exclude an influence from confounding variables, possible effects of age, gender, hand dominance and duration of formalin preservation were also studied (Table I). As the specimens were preserved in formalin for different durations it was necessary to determine whether such storage might have confounded any of the results by causing a time-related alteration in material stiffness.

**Statistical analysis.** An unpaired \(t\)-test was used to search for differences between normal and torn tendons. A one-way analysis of variance (ANOVA) with a Bonferroni multiple comparison test was used to compare individual tear classes and to account for a possible type I error associated with multiple statistical tests. Effects of gender and hand dominance were studied with unpaired \(t\)-tests. Correlation studies looking for an association between the modulus and the age and duration of preservation in formalin were analysed with a Pearson’s rank correlation. All tests were two-tailed and a \(p\)-value < 0.05 and \(\alpha < 0.05\) were considered significant.

GraphPad Prism 5 (Graph Pad Software, LaJolla, California) software was used. Ethical approval was obtained and informed consent was obtained from all patients.

**Results**

**Effect of tears.** A significant difference was detected between normal and torn rotator cuff tendons (Fig. 2), demonstrating that healthy tendons had a higher modulus and hence greater mechanical integrity than torn tendons (unpaired \(t\)-test, \(p = 0.003\)).

\(G' = \frac{\sigma}{\delta} \)
In order to further study the effect of rotator cuff tears on tendon modulus, we analyzed the data looking at each category of tear as a separate group. Tears were grouped by size into small, medium, large and massive (Fig. 3). Differences between the five groups were found to be statistically significant (ANOVA, p = 0.0039). The groups were compared with one another and the only significant paired differences detected showed that the moduli of normal tendons were significantly higher than those of massive tears (Bonferroni’s multiple comparison test, p < 0.01). Hence normal healthy tendon samples possessed statistically greater mechanical integrity that those from tendons with massive tears. A negative trend was apparent, with a decrease in the modulus as the size of the tendon tear increased, but this relationship was not significant (r = -0.698, p = 0.189).

**Influence of pre-operative factors.** There was no obvious difference between the four surgical groups for age, gender or hand dominance (Table I). The scatter of the data shows that there is no significant correlation between age and modulus (Fig. 4; r = 0.020, p = 0.846, α > 0.05). However,
this study was not powered to detect an effect of age on modulus. Nor did gender have any obvious correlation with modulus (t-test, p = 0.65), as no difference was seen between the male and female groups (Fig. 4b). Interestingly, hand dominance did not seem to have any effect on the mechanical integrity of rotator cuff tendons either. For all patients, we determined whether the operated shoulder was on the same side as their dominant hand. A graph of modulus related to dominance (Fig. 4c) did not reveal any association (t-test, p = 0.891). No significant effect of duration of preservation in formalin was seen (Pearson’s rank correlation, p = 0.089; Fig. 4d).

Discussion
Our study demonstrates that normal rotator cuff tendons have a significantly higher shear modulus than torn rotator cuff tendons, indicating that torn tendons have less mechanical integrity (p = 0.003). Ruptured tendons have high prevalence of degenerative change,\(^1\) which may translate to structural weakness. The finding that torn tendons have less mechanical integrity than normal tendons is important, and offers potential insight into high post-operative failure rates. Excessive tissue compression has been shown to induce fibrocartilaginous changes within supraspinatus tendon,\(^1\) which may not be able to withstand loading as well as intact tendons do. Alternatively, tendon tears may heal via formation of scar tissue,\(^2\) which is mechanically inferior to intact tendon. If the repair is formed in tissue at the edge of rotator cuff tears that has a lower modulus of elasticity, this tissue may have a reduced capacity to withstand the strain and mechanical loading that might be placed on the repair. There is little literature confirming that naturally torn human rotator cuff tendons are in fact weaker.

Our study demonstrates a trend between increasing tear size and decreasing mechanical integrity, although this was not statistically significant (r = -0.698, p = 0.189). This is a novel observation, as an effect of tear size has previously been seen in physiological and healing studies\(^9\) but not in mechanical studies of rotator cuff tears. The only individual paired difference detected was that massive tears were found to be significantly less stiff than normal tendons (p = 0.0031). The modulus did not distinguish between small, medium and large tears as expected. A number of studies have indicated that larger tears are more likely to re-rupture.\(^7\) Cofield et al\(^21\) reported that tear size was the most important determinant of post-operative strength. The edges of smaller tendon tears have higher reported metabolic

### Table I. The categories of specimens tested (n = 100), with patient characteristics and duration of preservation in formalin

<table>
<thead>
<tr>
<th>Category</th>
<th>Normal</th>
<th>All tears combined</th>
<th>Small</th>
<th>Medium</th>
<th>Large</th>
<th>Massive</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size of tear</td>
<td>-</td>
<td>-</td>
<td>&lt; 1 cm</td>
<td>1 to 3 cm</td>
<td>3 to 5 cm</td>
<td>&gt; 5 cm</td>
</tr>
<tr>
<td>Number of patients (n)</td>
<td>18</td>
<td>82</td>
<td>16</td>
<td>24</td>
<td>21</td>
<td>19</td>
</tr>
<tr>
<td>Mean age (yrs) (range)</td>
<td>58.8 (20 to 89)</td>
<td>65.2 (47 to 83)</td>
<td>66.7 (57 to 78)</td>
<td>64.5 (51 to 80)</td>
<td>64.3 (53 to 83)</td>
<td>66.4 (52 to 81)</td>
</tr>
<tr>
<td>Female:male (n)</td>
<td>9:9</td>
<td>31:51</td>
<td>6:12</td>
<td>11:13</td>
<td>9:12</td>
<td>5:14</td>
</tr>
<tr>
<td>Mean time in formalin (weeks)</td>
<td>7 (2 to 13)</td>
<td>7 (2 to 29)</td>
<td>6 (2 to 29)</td>
<td>7 (2 to 29)</td>
<td>8 (2 to 28)</td>
<td>7 (2 to 28)</td>
</tr>
</tbody>
</table>
Higher rates of healing have also been found in small tears, which could therefore provide greater structural and mechanical integrity. Significant variability of modulus was found in all tear size groups. This may explain why some small- and medium-sized tears re-rupture after repair despite having better viability than massive tears. Despite our large study size, by subdividing the tears in groups by size, the sample numbers may have been inadequate to detect a difference between the groups. The lack of detected difference may also be due to variability within this technique, although the repeatability of the test values was significantly high. More longitudinal data are needed to understand the rate of progression for differently sized tears; however, this study is cross-sectional and only offers insight at one time-point.

Although increasing age is associated with higher post-operative failure rates, an effect of age on the modulus of tendons was not demonstrated. No effect of age was also found by Fukuda et al., but this contradicts an early study by Reeves suggesting that the tensile strength of anterior capsular structures weakens with age. Our present study was inadequately powered to detect any subtle effects of age or other pre-operative factors, as this was not the focus of the study. As the incidence of rotator cuff tendon tears increases with age, it is difficult to find tears or age-matched controls over a wide range of ages to address this question accurately.

Our study offers a unique assessment of human diseased tissue taken intra-operatively from different stages of rotator cuff pathology. To date, the majority of mechanical testing of rotator cuff tendons has relied on animal models or human cadavers, which may not be directly applicable to human rotator cuff tendons. The anatomy, structure and mechanics in quadruped animals are different from those in bipedal humans. The degenerative and biological changes preceding most tears, and the response following tears, are
a critical element in healing and tear propagation, and artificially created tears in *ex vivo* tendons may not replicate these important parameters.

Developing an analytical technique that uses the limited number of small tendon samples that can be ethically collected is critical in achieving our stated aim of understanding human disease. Using a rheometer instead of the traditional tensile tester minimised clamping effects by subjecting samples to oscillatory deformation under compression. In tensile testing there is a wide variation in the method of gripping the specimens, owing to the difficulty of achieving a uniform and effective hold on the collection of the partially independent sub-fibres. Any failure of gripping will result in a decrease in measured stiffness and strength. Dynamic shear analysis may be an answer to this problem and could be extended to study other soft-tissue models. This analysis provides data on relative differences in very small tendon specimens rather than absolute values. Although the type of shear used in this study is a relevant model, it cannot comprehensively simulate the complex biomechanics of the shoulder. However, the aim of this study was to establish relative differences between different groups, which dynamic shear analysis permits.

Characterising the shear modulus of rotator cuff tendons is relevant, as the shoulder is a complex joint subjected to multiple forces, including shear. Rotator cuff tendons display anisotropy and region-specific mechanical variations, with anterior supraspinatus strips demonstrating a higher ultimate load and stress. Our study was designed only to test shear responses and does not quantify uniaxial tensile properties, which are the predominant strain pattern seen in shoulders. However, shear properties are related to tensile properties, and studies of numerous heterogeneous anisotropic materials have demonstrated that tensile properties are related to shear mechanical parameters such as shear modulus and bulk modulus. Previous studies have also shown the importance of testing tendons in subfailure ranges which are consistent with *in vivo* loading, as was done in this study, rather than just focusing on the linear region of loading and at failure.

Such a large number of human specimens for mechanical testing of rotator cuff tendons has not been collected before. In order to overcome logistical difficulties in collecting specimens from different locations and times, it was necessary to place them in formalin for storage so that testing was undertaken in uniform conditions. We assumed that any effect of formalin would be the same for all specimens, and any differences between samples would be inherent to their material properties and not their preparation. Although fixation of tissues prior to testing is not the standard, we have found no effect due to the time spent in formalin (p = 0.246). No method of storage for human tissues is without problems, and even the commonly reported technique of freeze-drying has been shown to alter the mechanical properties of tendons and to reduce Young’s modulus. Future studies can build on our preliminary investigation by looking at tendons preserved by freeze-drying, as well as testing fresh samples.

Although this pilot study has shown differences in the shear mechanical properties of rotator cuff tendons, further investigation is required to understand the clinical implications of differences in shear moduli. If differences in shear moduli have a relationship with failure rates, it may be possible to use dynamic shear analysis of rotator cuff biopsies to assess the strength of different forms of repair, or for early identification of mechanically weakened tissue that might be unable to support a simple sutured repair and might warrant augmentation. If a threshold of ‘integrity’ of the cuff tissue could be established, dynamic shear analysis could potentially help to delineate diseased tissue which appears macroscopically normal, to differentiate between which partial tears should be debrided and which need to be repaired.

We conclude that there are important differences in the mechanical properties of normal and torn rotator cuff tendons, as demonstrated by dynamic shear analysis. This technique could have an application in defining the most appropriate treatment for rotator cuff tears.

No benefits in any form have been or will be received from a commercial party related directly or indirectly to the subject of this article.

References