The Compressive Behavior of the Human Glenoid Labrum May Explain the Common Patterns of SLAP Lesions

Chris D. Smith, M.B., B.Ch., M.R.C.S., Spyridon D. Masouros, Ph.D., Adam M. Hill, M.B., Ph.D., Andrew L. Wallace, F.R.A.C.S., Andrew A. Amis, D.Sc.(Eng), and Anthony M. J. Bull, Ph.D.

Purpose: The aim of the study was to define the normalized compressive stiffness (modulus) of the glenoid labrum around its circumference and to characterize the difference in modulus between different areas. **Methods:** Sixteen fresh-frozen cadaveric shoulders were harvested and dissected down to the glenoid labrum. Any specimens with significant degenerative changes were discarded, leaving 8 labra for testing. The labrum was divided into 8 segments, to allow comparison around its circumference. A uniform testing specimen was produced from each area by use of a microtome. Each specimen measured 3 × 1 mm in cross section and was 6 mm in length. Indentation testing was conducted in a controlled environment of 100% humidity at 37°C ± 1°C. **Results:** We obtained 52 test samples from 8 labra. The mean modulus of the glenoid labrum was 69.7 megapascal (standard deviation, 36.2 megapascal). The anterosuperior portion of the labrum had a higher modulus than the posteroinferior portion ($P = .0075$). **Conclusions:** This study has shown that the human glenoid labrum's compressive behavior varies around its circumference. The greater modulus of the anterosuperior portion of the labrum supports the theory that this area is anatomically different from the rest of the labrum and resists compressive loads. **Clinical Relevance:** These results may explain why the common type of SLAP lesions seen show failure at the interface between the labrum and the glenoid rather than within the substance of the labrum itself. **Key Words:** In vitro—Material properties—Compressive testing.

SLAP lesions of the superior aspect of the glenoid labrum are classified as types I through X.[1-4] These can be divided into 2 broad categories: those that are intrasubstance tears and those that fail at the interface between the labrum and underlying glenoid or detachment. Type II consists of a detachment of the labrum from the underlying glenoid; type VI is a combination of a detachment and a midsubstance tear. Most SLAP lesions found at arthroscopy are type II lesions,[2,4-7] and where the injury mechanism is known, it is found to be compression and pure traction, suggesting impingement between the humeral head and the glenoid or torsional tension along the biceps anchor.[8,9] It is thought that a tight posterior capsule and the development of a glenohumeral internal rotation deficit comprise the critical first stage in the development of SLAP lesions in throwing athletes.[10] Biomechanical studies have confirmed that pure traction and external rotation with abduction will re-create a SLAP lesion.[11-13] No studies have tested the compression mechanism. In addition, although the tensile properties of the labrum are known to vary around the labrum,[14] there has been only 1 study that measured the compressive properties of the labrum.[15] The interpretation of this study is limited in that the tissue was

From the Departments of Bioengineering (C.D.S., S.D.M., A.M.H., A.M.J.B.), Mechanical Engineering (C.D.S., S.D.M., A.A.A.), Biosurgery & Surgical Technology (A.M.H.), and Musculoskeletal Surgery (A.L.W., A.A.A.), Imperial College London, and Shoulder Unit, Hospital of St John & St Elizabeth (A.L.W.), London, England.

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Address correspondence and reprint requests to Anthony M. J. Bull, Ph.D., Department of Bioengineering, Imperial College London, Room 4.31 Royal School of Mines, South Kensington Campus, London SW7 2AZ, England. E-mail: a.bull@imperial.ac.uk

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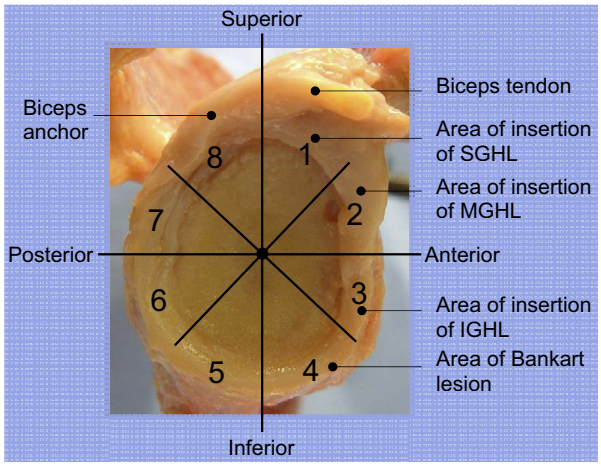

Figure 1. Gross anatomy of glenoid labrum. (SGHL, superior glenohumeral ligament; MGHL, middle glenohumeral ligament; IGHL, inferior glenohumeral ligament.)

embalmed and formalin fixation is known to change the mechanical properties of tissues.[16]

Therefore the aim of this study was to examine the biomechanical behavior of the human glenoid labrum under compression in fresh-frozen cadaveric shoulders and to test the specific hypothesis that there is a difference in the compressive stiffness between the superior and inferior parts of the labrum. This would explain why SLAP lesions would appear in some regions of the labrum more than in others when compressed during impingement injury mechanisms.

METHODS

This study was approved by a local ethics committee, and 16 fresh-frozen cadaveric shoulders were obtained from a tissue bank. All the shoulders had been harvested with the scapula and proximal half of the humerus intact. The specimens were stored at −20°C when not in use and were sprayed with physiologic saline solution during dissection and testing. All specimens were thawed at room temperature overnight before use.

Each specimen was initially dissected with preservation of the rotator cuff musculature. The cuff was excised from its insertion on the humerus, to allow safe disarticulation of the joint without intra-articular iatrogenic damage. The articular surfaces were graded according to the Outerbridge classification,[17] and the gross anatomy and dimensions of the labra were recorded with Vernier calipers. Any specimens that showed degeneration tears or fibrillation of the labrum or degenerative changes greater than grade I of either articular surface were withdrawn from the study. After initial inspection, 8 specimens had significant degenerative changes and were withdrawn from the study.

The remaining 8 labra, from 4 right and 4 left shoulders, had a mean age of 61 years (range, 47 to 70 years). Each labrum was harvested carefully from the underlying glenoid surface and divided into 8 segments around its circumference (Fig 1). Each section was straightened out and attached by use of a cryoclamp onto a microtome for accurate freeze fracturing of the sections into 1-mm-thick slices in a plane parallel to the collagen fibers. The freeze fracture was accomplished with high velocity. Rapid freezing/thawing under defined conditions is known to have no effect on load-elongation curves of spinal longitudinal ligament test samples.[18] There is no similar information on cartilage, labrum, or meniscus.

Each slice was remounted to the microtome by its free edge and cut again. This produced a testing sample with a width of 3 mm, a thickness of 1 mm, and a length between 6 mm and 8 mm (Fig 2). All the test samples were measured directly after cutting while still frozen by use of electronic calipers (Mitutoyo, Andover, England), and any that deviated from the desired dimensions by more than 0.1 mm were rejected from further testing.

All testing was carried out on an Instron materials testing machine (model 5565; Instron, Norwood, MA), with accompanying Merlin software (version 4; Instron). A 10-N load cell (accurate to within ±0.25% of load applied) was used; this was calibrated before each testing session. An environmental chamber that could regulate the temperature to 37°C ± 1°C and maintain 100% relative humidity was used during testing.[18]

Each test sample was inserted into a stainless steel

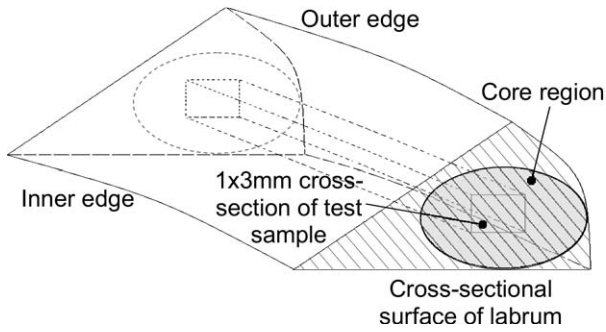

Figure 2. Diagram of a single glenoid portion with test sample orientation within core region.

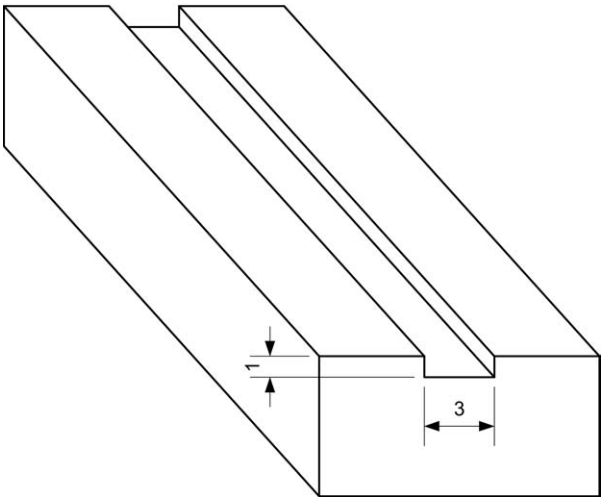

FIGURE 3. Image of well used for testing. The sample's dimensions allow for an exact fit to the well's slot. The indenter is impermeable and 3 mm in diameter.

trough with a depth of 1 mm and width of 3 mm, allowing an exact fit of the test sample (Fig 3). Both ends of the test samples were not enclosed, allowing some free movement of fluid in and out of the sample during testing. The indenter used was a 3-mm-diameter stainless steel sphere.

The test sample was allowed to adjust to the environmental conditions for 5 minutes before testing. The specimen was tested in compression so that the indenter was placed perpendicular to the long axis of the fibers as follows:

1. Precycling with force and displacement control at a 10-mm/min displacement rate. The specimen was cycled between 0 mm and a 0.5-N load until the hysteresis curves were overlapping. (Zero displacement was defined by manually lowering the indenter onto the test sample until a load was recorded. Overlapping curves were defined as a difference of less than 0.01 mm measured at the ascending 0.25-N load position between 2 consecutive cycles.)
2. Rezeroing the displacement. A load of 0.01 N was then placed on the preconditioned test sample so that a new zero position could be documented accurately. (This "tare load" was used because of the very low stiffness response of biologic tissues with low loads [commonly called the toe region]; the tare load allows a robust repeatable zero displacement to be established.)
3. Final precycling. The main testing commenced with a further 10 precycles to 0.5 N. (This ensured complete preconditioning after the readjustment of the sample.)
4. Tensile loading. The test sample was loaded up to 1.5 N.
5. Stress relaxation. The test sample was allowed to undergo stress relaxation for 5 minutes by keeping the displacement constant throughout this time. (In pilot testing a 5-minute period of stress relaxation was enough for all samples tested to reach an equilibrium state.)
6. Tensile loading. The test sample was returned to zero displacement and was loaded to 3 N.
7. Stress relaxation. A second 5-minute period of stress relaxation was allowed.
8. Tensile loading. The test sample was returned to zero displacement and was loaded to 5 N.

A typical load versus displacement graph is presented in Fig 4.

A compressive modulus for each test sample was determined from the linear portion of the stress-strain curve at final loading, that is, after the second period of stress relaxation. A tangent compressive modulus was similarly calculated before the first and second periods of stress relaxation. The strain was recalculated after the second stress relaxation because of the change in thickness of the sample. The modulus was obtained by use of linear regression analysis.

The hypothesis was tested by comparing the compressive modulus at final loading for each possible combination of 4 adjacent portions against the other 4 portions for a significant difference by use of a 1-tailed paired Student t test with an α level of 0.05. This resulted in 4 comparisons being made, with a Bonferroni correction applied. Statistical significance

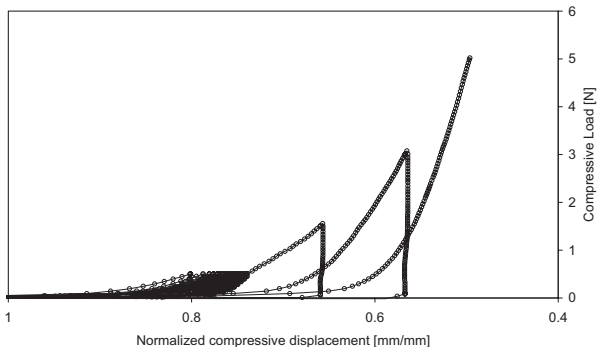

FIGURE 4. Typical graph of compressive load against compressive displacement that has been normalized (in terms of thickness) (loading–stress relaxation–unloading–loading–stress relaxation–unloading–loading).

TABLE 1. *Mean Poststress Relaxation Modulus for Each Portion of Glenoid Labrum (N = 52)*

	Portion 1	Portion 2	Portion 3	Portion 4	Portion 5	Portion 6	Portion 7	Portion 8
Tangent compressive modulus (MPa)	79.2 (19.4)	85.7 (78.5)	83.1 (46.0)	72.3 (26.5)	54.4 (15.4)	51.3 (31.9)	56.9 (27.8)	79.7 (26.1)

NOTE. Data are given as mean (SD).

was therefore shown if $P < .0125$. Statistically significant results are presented.

RESULTS

Because of the varying dimensions among labra, a reliable test sample that had a consistent 3 × 1–mm cross section along its whole length could not be obtained for all 8 positions on each labrum. This resulted in 52 out of 64 potential test samples from 8 labra.

The mean compressive modulus (after stress relaxation) of the glenoid labrum was 69.7 megapascal (MPa) (standard deviation [SD], 36.2 MPa). The mean poststress relaxation tangent compressive modulus for each portion of the glenoid labrum is presented in Table 1. The tangent compressive modulus after the first period of stress relaxation increased by a mean of 22.9 MPa (SD, 6.2 MPa) ($P < .001$) compared with prior stress relaxation and increased by a further 32.9 MPa (SD, 32.9 MPa) ($P < .001$) after the second period of stress relaxation.

For the final compressive modulus, portions 1 through 3 and 8 were significantly stiffer than portions 4 through 7 ($P = .0075$). The posteroinferior quadrant had a significantly lower modulus than the anteroinferior quadrant ($P < .01$).

DISCUSSION

The principal finding of this study was that the inferoposterior part of the labrum has a lower compressive stiffness than the anterosuperior quadrant.

As expected with biologic tissue, the SDs are large, especially for portion 2, which is known to have the most anatomic variation.[5,19,20] We believe our data are the only data available on fresh, hydrated labral tissue; prior work has been performed with formalin-fixed tissue,[15] which is known to be stiffer than unfixed tissue.[16] Although not comparable, this prior work did show that the compressive modulus for the superior half of the labrum was significantly higher than that of the inferior labrum.

To examine the dynamic viscoelastic behavior of the labrum under cyclical compressive loading and, as such, mimic the pattern of loading experienced through activities of daily living, the specimens were cycled followed by a period of stress relaxation and moduli compared both before and after equilibrium was reached under a constant load. Activities of daily living are a mixture of constant load and constant displacement, interspersed with varying loading rates.[21] During these activities, soft connective tissues of joints are reported to work in the toe regions of their stress-strain curves.[22-24] The tangent modulus at the end of the first period of stress relaxation was significantly less than that at the end of the second stress relaxation period, which in turn was significantly less than the final elastic modulus. As such, the labral tissue stiffened through each period of stress relaxation, most probably as a result of net fluid extrusion.

Previously, the superior region of the labrum (positions 1 and 2) has been shown to have a significantly lower tensile elastic modulus and yield stress when compared with the inferior region (positions 4 and 5)[14] (Fig 5). This suggests that the anterosuperior part of

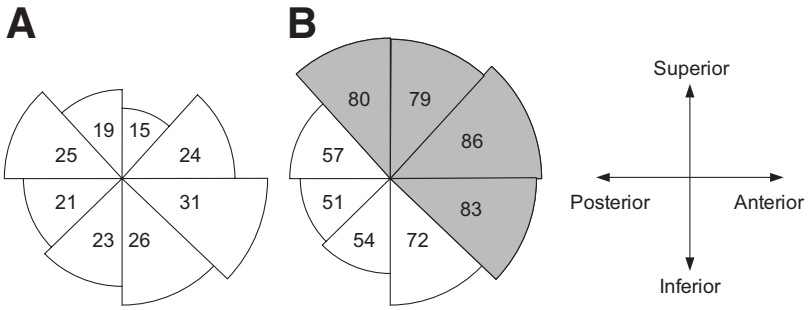

FIGURE 5. Mean values for (A) tensile modulus and (B) indentation stiffness at each portion of labrum after stress relaxation, averaged among specimens. All values are in megapascals. The tensile modulus values are from Smith et al.[14]

the labrum is good in compression and weak in tension and anatomically different from the remainder of the labrum.

It could be concluded that this increased resistance to compression is why most SLAP lesions involve failure between the labrum and the glenoid (i.e., detachment), rather than a midsubstance failure. The superior labrum may be able to resist the proximal subluxation of the humeral head pinching it against the glenoid until failure occurs at this interface. However, to confirm this, further work needs to be aimed at re-creating push-off lesions of the superior labrum to determine whether the familiar patterns of SLAP lesions are re-created.

The previous work suggesting a reduced tensile elastic modulus (equivalent in definition to the compressive modulus defined in this article) in this region may be thought to explain the intrasubstance tears as pull-off lesions.[14] However, the position of failure is between parallel fibers in a type III or IV lesion, whereas the direction of tensile testing in the published literature was along the direction of the fibers. No work has been produced on the radial tensile properties of the labrum.

The anterosuperior region is the most variable part of the labrum, which appears to be detached in utero.[25,26] This difference in utero may be the cause of the numerous variations seen in that part of the labrum in the adult including a complete absence, a sublabral foramen, a sublabral recess, and the Buford complex.[20,27-31] These anatomic variations may make certain patients more susceptible to tears in this region; the Buford complex has been associated with a higher rate of SLAP lesions.[32,33]

It could be hypothesized that intrasubstance lesions and detachment lesions have different mechanisms of injury and that it is unlikely for a type II lesion to progress to a type III lesion if unaddressed, because the point of failure is different.

These results aid the clinician in determining what forces will cause pathologic injuries and the likely pattern of injuries produced. They also show the forces that any repair is likely to be subjected to after surgery.

This study was not without its limitations, and we believe that there are a number of ways in which it could be improved. For example, we found that the number of precycles before reaching equilibrium was not consistent; this may have been because of the previous long-term preservation of the tissues.[34] Therefore we would propose the immediate use of unfrozen specimens in the future. There are a number of ways to reduce the large standard deviations found; these include studying specimens from a small, relevant age range[35] or significantly increasing the number of specimens. These suggested improvements and hence acknowledged limitations do not negate the results of this study.

CONCLUSIONS

This study has shown that the human glenoid labrum's compressive behavior varies around its circumference. The greater modulus of the anterosuperior portion of the labrum supports the theory that this area is anatomically different from the rest of the labrum and resists compressive loads.

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