Biotribology: The Acetabular Labrum

The sealing function of the acetabular labrum and its effects on the cartilage of the femoro-acetabular joint

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Introduction

In recent years, the management of hip and groin injuries has broadened significantly due to advancements in arthroscopic procedures. Minimally invasive surgical techniques allow a relatively fast recovery for athletes in highly competitive environments or a return to normal activity without pain. The advancements in magnetic resonance imaging (MRI) help explain the source of pain stemming from damage or deformities interior to the femoro-acetabular joint. A major result of advanced imaging techniques was the evaluation of acetabular labral tears. Once left untreated, the acetabular labrum became a main focus for research due to a lack of understanding in regard to its function.

Currently, the arthroscopic technique for labral tears is excision, otherwise known as debridement, which is a complete or partial removal of the torn area, and an attempt to repair the labrum. Surgical methods are typically reserved for patients presenting with pain that has not responded to physical therapy as well as an identifiable pathology for a labral tear shown by an examination. Research into the function of the acetabular labrum will provide rationale for adapting surgical techniques to ensure the physiologic functions of the labrum are not compromised.

The objective of this paper is to explore the proposed function of the acetabular labrum as a seal for the femoro-acetabular joint, based on in-vitro and finite element studies. Taking a tribological approach to the literature, the potential increase in wear rate and changes in contact stresses interior to the joint due to a torn or surgically debrided labrum will be evaluated. As will be shown through a review of the literature, it is accurate to consider sealing a primary function of the acetabular labrum.
Anatomy and Function of the Labrum

The labrum in the human femoro-acetabular joint, located in the capsule of the hip, is attached to the circumference of the acetabular perimeter. As shown in Figure 1, the transverse acetabular ligament is connected to the labrum both anteriorly and posteriorly. The labrum is thinner in the anterior inferior section and thicker, with a slight roundness in appearance, in the posterior section. Free nerve endings have been identified within labral tissue, which potentially explains the pain pathway in a patient with a labral tear.¹

Like many joints, the vascular pattern of the labrum is distinct, with the majority of the vascular supply coming from capsular vessels in the surrounding hip capsule. The articular surface of the labrum has been shown to have decreased vascularity and has limited synovial membrane covering. Arthroscopic visualization of an injured labrum has shown extensive penetration of the vascular tissue through the labrum in its entirety, which suggests the labrum may have a healing potential not previously recognized.¹

Figure 1: (A) Diagram of the acetabular labrum² (B) High-powered photo of the anterior-superior region of the labrum³. Vascular regions are shown in dark red, mainly away from the articulating surface.
Peterson et al. have examined the structure of the acetabular labrum in detail. Using various techniques, the authors were able to identify the following two distinct tissue types present in the labrum: fibrocartilage and dense connective tissue. The fibrocartilage is mainly found in the internal region near the articulating surface of the labrum and is comprised of type II collagen, which is the fibrous connective tissue that makes up cartilage. The dense connective tissue is found mostly in the periphery of the labrum and is comprised of collagen similar to the interior region. However, the collagen present in the dense connective tissue was verified as type I and type III, which is found mostly in ligaments and other connective tissues in the body. The authors speculate about the difference in makeup of the labrum; whereas the compressive and shear stresses seen in the articulating zone result in the formation of fibrocartilage, only dense connective tissue can withstand the tensional stresses experienced in the exterior region of the acetabular labrum.¹

Seldes et al. further defined the anatomy of the labrum by describing attachment points of the labrum to the interior and exterior of the femoro-acetabular. As seen in Figure 2, on the interior, a transition zone is present between the fibrocartilagenous region of the acetabular labrum and the articular cartilage, which is approximately 1 to 2 millimeters in thickness. The exterior of the labrum is attached to the acetabulum through a bony projection made of calcified cartilage.¹
In an attempt to fully understand the pathology and study the range of surgical techniques to remove pain associated with acetabular labrum tears, experiments and finite element modeling have been used to explain the labrum’s function as a part of the femoro-acetabular joint. The results demonstrate various functions of the joint, one of the most important shown by Ferguson et al. through a finite element model is the labrum’s function as a seal for escaping fluid under normal loading between the articular cartilage on the femoral head and acetabulum. The labrum effectively prevents fluid from escaping the joint in order to retain a thin fluid film between the articulating surfaces allowing lubrication and transfer of the load via fluid pressure, which prevents premature wear of the cartilage surfaces by reducing cartilage consolidation. The authors attempted to replicate the findings of the model using an in vitro experiment, with similar results. Song et al. used experimental results on cadaveric hips to show the friction increase from partial removal or complete removal of the acetabular labrum, further validating the hypothesized sealing function.

**Finite Element Modeling and Results**

Cartilage deformation can be linked to fluid flow found in soil consolidation theory. Dr. Maurice A. Biot formulated a theory on consolidation in which there are three phases of soil
settling: water flowing out of soil directly under load, water flowing from loading to unloaded regions, and the restraining effect of the unloaded region upon the loaded regions. Similarly, cartilage has been shown to have mechanical behavior governed by its biphasic structure, which is a mixed solid and fluid phase within a fluid-bathed environment. This is particularly important when modeling cartilage material and when considering the acetabular labrum as a functional seal for the fluid. The biphasic model of articular cartilage typically represents a soft porous elastic solid permeated by water. This model is able to account for the time-dependent behavior of cartilage deformation as a result of the fluid’s resistance to interstitial flow and the permeability of the cartilage.

Ferguson et al. attempted to verify the proposed function of the acetabular labrum as a seal based on results of cadaveric studies performed by Terayama et al. in which a thin film (0.2 to 0.6 millimeters thick) was confirmed to remain during an application of a 1000-1500 N compressive load across the joint. As shown in Figure 3, in these joints, the labrum remained in tight contact with the opposing femoral cartilage surface, which demonstrates the behavior of a sealing mechanism.

Figure 3: From the joint loading experiments of Terayama et al. The acetabular and femoral cartilage surfaces are shown and do not come into direct contact.
Ferguson et al. used an axisymmetric finite element model to approximate the study by Terayama et al. ABAQUS 5.7 was used for the analysis based on its ability to model contact stresses and poroelastic (biphasic) materials. The articular cartilage layers of the acetabulum and femur were modeled as isotropic poroelastic materials. The material properties used were based on previous studies of cartilage biomechanics: elastic modulus $E=0.467$ MPa, Poisson’s ratio $\nu=0.167$ of the drained solid matrix, permeability $k=7.358 \text{E-8 mm/s}$, specific weight of the pore fluid $\gamma=9.81 \text{kN/m}^3$ and solid fraction as 20% of the total tissue volume. The labrum was modeled as a transversely isotropic poroelastic material due to its highly oriented structure of circumferential collagen. The models varied circumferential stiffness values of the labrum from 50-200 MPa based on the meniscus of the knee studies. The stiffness of the labrum was assumed to be the most important factor contributing to the function of the labrum as a seal.

The hip joint geometry was based on average measurements from MRI with cartilage layers of 3 millimeters thick. The underlying bone of the acetabulum and femur were modeled as rigid and impermeable, which is a valid assumption when comparing the rigidity and permeability of bone with cartilage. Initial contact between the labrum and articular cartilage of the femur was set, leaving an initial fluid layer thickness of 0.4 mm between the femur and the acetabulum. The fluid layer was modeled using poroelastic elements with very low stiffness, high permeability, and high water content to simulate the incompressible fluid which can develop hydrostatic pressure.\(^4\)

A compressive load at the symmetry line of 1200 N was applied and held. The contact pressure between the labrum and femur was compared to the pressure in the fluid layer. If at any time the pressure in the fluid layer exceeded the contact pressure at the labrum and cartilage interface, the labrum would no longer function as a seal. The model was also analyzed without a
fluid layer. Figure 4 details the symmetry in the model as well as the mesh of the different components.

![Figure 4: Axisymmetric finite element mesh of the femoro-acetabular joint including the cartilage layers (light grey) and labrum (dark grey). For clarity, elements are shown reflected about the axis of symmetry.](image)

As expected, the results showed that for a circumferential stiffness in the labrum greater than 100 MPa, the labrum would function as a seal and greatly reduce the resultant stresses in the articular cartilage solid matrix. As the load was applied, the cartilage layers gradually approached each other as the fluid was redistributed in the joint but a thin layer of fluid remained causing the load to be transferred between the cartilage layers via interstitial pressure, not direct solid contact. The layers of cartilage did not contact until 200 seconds into the analysis. As the stiffness of the labrum was decreased, the labrum became more compliant and would not function as a seal due to greater pressure in the interstitial fluid than the contact pressure between the labrum and femur. Without the presence of fluid, there was direct contact between the femoral and acetabular cartilage and a larger portion of the applied load was transferred through the joint from direct solid contact, as expected from removing the fluid layer in the analysis.

While the model by Ferguson et al. showed that the labrum acts as a functional seal, the authors used a separate model to study the influence of the labrum over a time period of 0 to 10,000 seconds on the rate of cartilage layer consolidation, stresses in the cartilage solid matrix, and the fluid pressure in the cartilage layers for models with and without the labrum. The model
incorporated a coronal slice of the hip, which is a view that divides the body into ventral and dorsal sections (belly and back). Using similar material properties for cartilage and a varying circumferential stiffness of the labrum, the model applied a constant compressive load which created a contact pressure in the acetabular cartilage equal to that calculated by an axisymmetric poroelastic joint contact model subject to a load of 0.75 times the bodyweight. A major difference between the models is there is not an initial fluid layer; the articulating surface cartilage on the acetabulum is modelled congruent to the femur cartilage, as shown in Figure 5.\(^5\)

![Figure 5: Plane Strain finite element mesh of the acetabulum (1), femoral (2) cartilage surfaces, and labrum (3). The circumferential (out-of-plane) stiffness of the labrum is simulated with in-plane truss elements. Sample points for output are A-C.\(^5\)](image)

The results from the analysis showed the influence of the labrum on the loading of the femoro-acetabular joint. After application of the load, the femoral head moved superiorly inside the labrum. Due to the reinforcement of the pelvic bones, there was also lateral movement of the femoral head inside the joint. The initial displacements increased over time from the interstitial fluid being forced from the joint, otherwise known as creep. The rate at which the femur approached the acetabulum, or the creep-consolidation rate, was up to 40% faster in the joint without a labrum. After 10,000 seconds, the cartilage layers had compressed 35% more in the
analysis without the labrum including a greater lateral displacement of the femur, likely resulting from the loss in depth of the joint with removal of the labrum.

The magnitude of the total contact pressure, stress in the solid matrix, and the pressure in the interstitial fluid, increased without the presence of the labrum and was less uniform over the contact surface, as shown in Figure 6. The contact area was modified with labrum removal, resulting in a shallower cavity resisting movement of the femoral head, which explains the shift in the pressure distribution.

Figure 6: (a) Total contact pressure exerted by the femoral cartilage on the acetabular cartilage at t=1000 seconds. Total contact pressure with the labrum is in dark grey while the total contact pressure without the labrum is in light grey. The analysis shows a higher total contact pressure without the labrum. (b) Solid contact stresses, interstitial fluid pressures, and total contact pressure are shown for peak analysis results. The percentage of load represents the load carried by the fluid.²

Removal of the labrum from the analysis not only affected the short term response of the joint to load, but also the time dependent creep-consolidation of the cartilage. The solid contact stresses increased over time due to the movement of fluid from the joint. As shown in Figure 7 below, the solid contact stresses were 64% higher at t=1000 seconds and 92% higher at t=10,000 seconds without the presence of a labrum. The increase in the solid contact stress is likely due the labrum acting as resistance to the flow path for the fluid moving out of the joint.
The results of both finite element models show a correlation of the assumed function of the labrum as a seal to the femoro-acetabular joint. The increase in contact pressure in the cartilage matrix detailed in the analysis and the limited lubrication shown in the absence of the labrum will increase friction between the articulating surfaces. The increase in friction will lead to accelerated wear in the joint with rotational movements of the femur. Experimental data will serve to validate the assumptions and results proposed by the models.

**Experimental Results**

In order to view the effect of labrum resection on inter-articular pressure in the femoro-acetabular joint and cartilage consolidation with time, Ferguson et al. performed an in-vitro experiment in which a compressive load was applied to hip joints in a laboratory environment. The experiment was carried out by placing a pressure transducer into the fat pad of the fossa, which is located past the transverse acetabular ligament. The pressure transducer was intended to measure the fluid pressure within the inter-articular space of the joint in lieu of the contact pressure between the articular cartilages. The pressure measured in the fossa is assumed to be the

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Figure 7: Solid contact stresses are plotted on the cartilage contact surface for t=1000 seconds (a) and t=10,000 seconds. (b) The stresses from the model with the labrum are in dark grey while the stresses with the labrum removed are in light grey.
result of fluid pressure only due to its very low stiffness and limited ability to carry loads. The applied force was carried out via a hydraulic actuator and the entire testing apparatus rested on a ball-bearing table to remove transverse loads during the experiment.6

The following series of five test steps was performed in sequence on each cadaveric joint: one preconditioning period with a constant load, one period with a constant load, one period with a cyclic load, one period with a constant load after excision of the labrum, and one period with a cyclic load after excision of the labrum. The constant load used was 0.75 times the bodyweight and the cyclic load varied by ±0.25 times the bodyweight from the constant load. Care was taken between tests to ensure fluid had returned to the joint prior to the next step to prevent testing inaccuracies. The pressure in the joint was recorded and linear displacement of the actuator, representing the cartilage consolidation, was recorded over the one hour time period for each test step.6

The results, shown in Figure 8, revealed a large difference between the pressure and cartilage consolidation before and after labrum excision. Similar results were found for the constant load and cyclic loads. The peak pressures occurred immediately after the load was applied and gradually decayed from there as the fluid was redistributed within the joint. The maximum pressures were 541 ±61 kPa with the labrum intact during constant loading, 216 ±164 kPa with the labrum removed during constant loading, 550 ±56 kPa with the labrum intact during cyclic loading, and 195 ±145 kPa with the labrum removed during cyclic loading. For consolidation rates and total consolidation, the experiments showed the initial consolidation rate for loading with an intact labrum was significantly lower than after labrum excision and the total consolidation (displacement) was much larger after labrum excision.6
The significance of these results is that the increase in pressure shows that the fluid carries a large portion of the load instead of the solid cartilage. This, in turn, mitigates loads at a faster rate as the interstitial fluid flow causes the joint to behave like a shock absorber as the fluid is redistributed in the joint. It appears that the reduction in the total cartilage consolidation as detailed by the smaller displacement with an intact labrum is resultant from the sealed fluid in the joint. This is to be expected based on the finite element analysis referred to above and performed by Ferguson et al., detailing the presence of a thin layer of fluid after loading of the hip joint. These results serve as further justification of the proposed function of the labrum as a seal.

In an attempt to determine the friction increases within the femoro-acetabular joint due to labral resection, Song et al. validated the conclusions presented by Ferguson et al., in both the finite element models and experimental results, with regard to the sealing function of the labrum. The experiment used a technique to measure the resistance to rotation at the articular cartilage surface with undamaged, partial, and complete resection of the labrum tissue. Details of partial
resection and complete removal of the labrum are shown in Figure 9. An axial load was applied, creating compressive stresses in the joint and then a rotational displacement. The data was analyzed based on a resistance to torque from the rotational displacement, which is linearly proportional to the static friction of the femoro-acetabular joint.\(^7\)

![Figure 9: (a) Partial resection and (b) complete resection used by Song et al for resistance to rotation experiment](image)

The results showed that the resistance to rotation increased when the labrum is partially or completely removed, which supports the conclusion from Ferguson et al. that the labrum acts as a seal for the hip joint. Song et al. explain that the intact labrum seals the joint and retains the fluid to be utilized as a lubricant, which minimizes cartilage consolidation. A damaged labrum will be less effective as a seal, therefore causing increased friction in the hip joint that developed as a resistance to rotation in the experiment.

**Conclusions and Potential Topics for Further Research:**

Based on the literature presented in this paper, the function of the labrum is well established as a sealing mechanism for the fluid within the femoro-acetabular joint. The inter-articular contact pressures and cartilage consolidation has been shown to greatly increase in the
absence of a labrum or with a partial resection. Since cartilage is a biphasic material, with the majority of the load being transmitted through it by the pressure in the fluid, the lack of a seal will cause increased contact stress in the solid cartilage matrix. Well established tribological principles associate an increase in the normal load with an increase in friction and therefore, an increase in the wear rate between two contacting surfaces. Although an increase in wear rates to articular cartilage was not demonstrated experimentally, Song et al. was able to experimentally show the increase in friction from labral resection. This increase in friction between the articulating surfaces, resulting from a damaged or debrided labrum, can be correlated to a likely increase in the wear rate of cartilage causing pain in the joint, otherwise known as osteoarthritis.

The preceding literature review indicates that there are a variety of research opportunities that can further advance the understanding of not only the effect of labral tears on articular cartilage but the etiology of labral tears. Such areas of future research include:

- Utilizing a 3-D model in commercial finite element software to correlate biomechanics with labral tears. Although extremely complex, research on this topic will allow a better understanding of the factors that contribute to labral tears. The research might lead to development of surgical techniques or preventive physical therapy in patients that present with high-risk physiology. Ranawat and Kelly have already presented the case that bony impingement is a factor contributing to the early degradation of labrum tissue.¹

- Performing an endurance study in a biomechanical model in finite element software that specifically focuses on damage to the articular cartilage will be extremely beneficial. A significant number of athletes present with hip pain associated with labral tears and premature wear of articular cartilage. An attempt
to quantify the loading conditions occurring during various sporting activities will assist with further research into preventive physical therapy for specific sport functions that can cause abnormal wear on the labrum and articular cartilage.

- The potential for removal of the labrum and replacing with a synthetic material is an interesting topic which can be of extreme benefit to patients who present with labral tears. In situations where surgeons cannot access the degraded area, and are thus unable to repair the labrum, removal may be an option.

As demonstrated in this paper, studies show that the labrum is a vital component in preserving the function of the hip joint. With the ever increasing level of athletic performance and the longevity of the population, further research into preventing and repairing labral tears will benefit patients that are inflicted with pain that can be debilitating.
References:


