A Technique to Diagnose Partial and Complete Injuries of the Anterior Cruciate Ligament Using Ultrasound

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INTRODUCTION:
An improved method to diagnose partial and complete anterior cruciate ligament (ACL) injuries would complement promising reconstruction techniques: ACL regeneration and two-bundle grafts. In particular, the success of ACL regeneration is affected by how much the native ACL has degraded in the days following acute trauma and the ability to assess the ACL during the remodeling process. Both techniques could also be used to repair partial injuries. There are two current clinical approaches to directly assess the mechanical integrity of the ACL: manual examination of knee laxity and visual evaluation using magnetic resonance imaging. Early diagnoses are unreliable using either approach, and these approaches are not yet acceptable for clinical diagnosis of partial tears. The potential of new reconstruction techniques and the limitations of current diagnostic techniques motivate the need for a new technique that can diagnose ACL injury earlier, diagnose single bundle injuries and identify the injured bundle, and monitor the ACL remodeling process.

One potential method is ultrasound strain elastography (USE), which estimates strain within soft tissue by tracking motion in sequences of ultrasound images. It has the benefits of any ultrasonic method, namely that it is accessible, inexpensive, and noninvasive. Imaging the ACL with ultrasound and interpreting strain within the ACL, however, is difficult because the ACL has a complicated anatomy and mechanical behavior. For these reasons, an USE method for the ACL is particularly challenging. The viability of an USE method for the ACL hinges on the ability to capture consistent ultrasound images of the ACL and characterize the ACL's integrity from the resulting strain distributions.

We have developed a USE method for the ACL that can overcome these difficulties. Our technique has three unique features: pairing a clinically relevant drawer test with USE, consistent imaging of the ACL with ultrasound, and quantitative assessment of soft tissue directly from strain distributions using a statistical analysis. As a first step in validation and development of our proposed technique, it was hypothesized that our technique can be used to differentiate between normal, partially transected, and transected ACLs in vitro. This hypothesis was validated for sheep knees.

MATERIALS AND METHODS:
Eight sheep knees with the knee capsule intact were mounted to an in-house designed rig (Figure 1). For each knee, the ACL's tibial insertion was located with ultrasound through a window on the anteromedial side of the knee (Figure 2). The ACL was deformed by manually applying a drawer test and ultrasound RF data was saved for later analysis. Then, through an incision on the anterolateral side of the knee, an incremental cut was made to the transverse axis of the ACL near the midpoint of the ACL. The anterolateral incision was pinned closed and the procedure was repeated until the ACL was completely transected.

RESULTS:
Fifty strain distributions were generated from eight sheep knees: eight distributions generated from uninjured ACLs, thirty-four from ACLs with various partial injuries, and eight from transected ACLs (Figure 3). The resulting diagnostic decision tree predicted the amount of injury based on strain statistics with a root mean square error of 17% torn. Furthermore, the decision tree perfectly partitioned the normal and torn ACLs giving this technique a 100% specificity and sensitivity for diagnosing complete tears in this experiment.

DISCUSSION:
Results from this experiment validated the hypothesis that our proposed technique can be used to distinguish between normal, partially transected, and transected ACLs. Although the experiment was conducted in vitro, these results translate well to what is expected in vivo, since freehand imaging on the outside of the knee capsule and a manual drawer test were used. This decision tree may not generalize to other injuries as a result of the small data set and particularity of the induced injury. It may however still distinguish between injured and normal ACLs. Consequently, the resulting diagnostic decision tree is considered demonstrative and different statistical analyses are being investigated. Future studies will assess our technique on human ACLs in vivo and with a larger data set.

Figure 1: Sheep knee mounted to an in-house designed rig. Drawer tests could be applied to mounted knees in vitro.

Figure 2: Ultrasound image of a sheep's ACL. Consistent ultrasound images of the ACL's tibial insertion can be achieved and used to estimate strain within the ACL during application of a drawer test.

Figure 3: Strain distribution generated from a normal ACL. The color reflects percent strain in the direction of wave propagation, which in the picture corresponds with the vertical direction. These strain distributions were able to characterize normal, partially injured, and torn ACLs via a statistical analysis.