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Femoral entheseal shape and attachment angle as potential risk factors for anterior cruciate ligament injury

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ABSTRACT

Although non-contact human ACL tears are a common knee injury, little is known about why they usually fail near the femoral enthesis. Recent histological studies have identified a range of characteristic femoral enthesis tidemark profiles and ligament attachment angles. We tested the effect of the tidemark profile and attachment angle on the distribution of strain across the enthesis, under a ligament stretch of 1.1. We employed a 2D analytical model followed by 3D finite element models using three constitutive forms and solved with ABAQUS/Standard. The results show that the maximum equivalent strain was located in the most distal region of the ACL femoral enthesis. It is noteworthy that this strain was markedly increased by a concave (with respect to bone) entheseal profile in that region as well as by a smaller attachment angle, both of which are features more commonly found in females. Although the magnitude of the maximum equivalent strain predicted was not consistent among the constitutive models used, it did not affect the relationship observed between entheseal shape and maximum equivalent strain. We conclude that a concave tidemark profile and acute attachment angle at the femoral ACL enthesis increase the risk for ACL failure, and that failure is most likely to begin in the most distal region of that enthesis.

1. Introduction

Anterior cruciate ligament (ACL) tears are the most common knee ligament injury, occurring more than 250,000 times per year in the United States (Griffin et al., 2006; Spindler and Wright, 2008). Complete tears of the ACL often require surgical reconstruction and increase the susceptibility to knee osteoarthritis within 10 years of the injury (Lohmander et al., 2007; Kessler et al., 2008). These injuries are especially common in female athletes, who are two to five times more likely to sustain an ACL tear than their male counterparts (Swenson et al., 2013; Hewett et al., 2005).

There has been considerable interest in determining anatomical features that increase an athlete's risk of ACL injury. Several morphological characteristics have been correlated with ACL injury, such as steeper posterior tibial slope in the lateral tibial plateau (Simon et al., 2010; Hashemi et al., 2010; Beynnon et al., 2014; Sturnick et al., 2015) and smaller intercondylar notch width (Simon et al., 2010; Sturnick et al., 2015; Whitney et al., 2014). It has also been proposed that smaller cross-sectional area of the ACL is to blame for the increased injury rate of females compared to males (Chandrashekar et al., 2005; Anderson et al., 2001). However, to the authors' knowledge, no statistically significant correlation has been found between cross-sectional area and injury risk. Additionally, while these correlations might prove useful, they lack a mechanical analysis that supports their direct causation of ACL injury.

Clinically, the most common location for an ACL tear is at or near the femoral insertion (Zantop et al., 2007). The reasons for this region's susceptibility are not yet fully understood. Nevertheless, in vitro experimental studies have demonstrated that the ACL is particularly prone to failure at the femoral enthesis, especially in the posterolateral (PL) bundle (Lipps et al., 2013; Beaulieu et al., 2015b; Meyer et al., 2008).

Recently, Beaulieu et al. (2016) identified six main categories of human femoral entheses by the shape of their tidemarks on standardized histological sections (see Fig. 1). Beaulieu et al. (2015a) also quantified the angle of attachment of the ACL as it arises from lateral femoral epicondyle. The data from that study indicated that, at 15° of knee flexion, male specimens, on average, have a larger attachment

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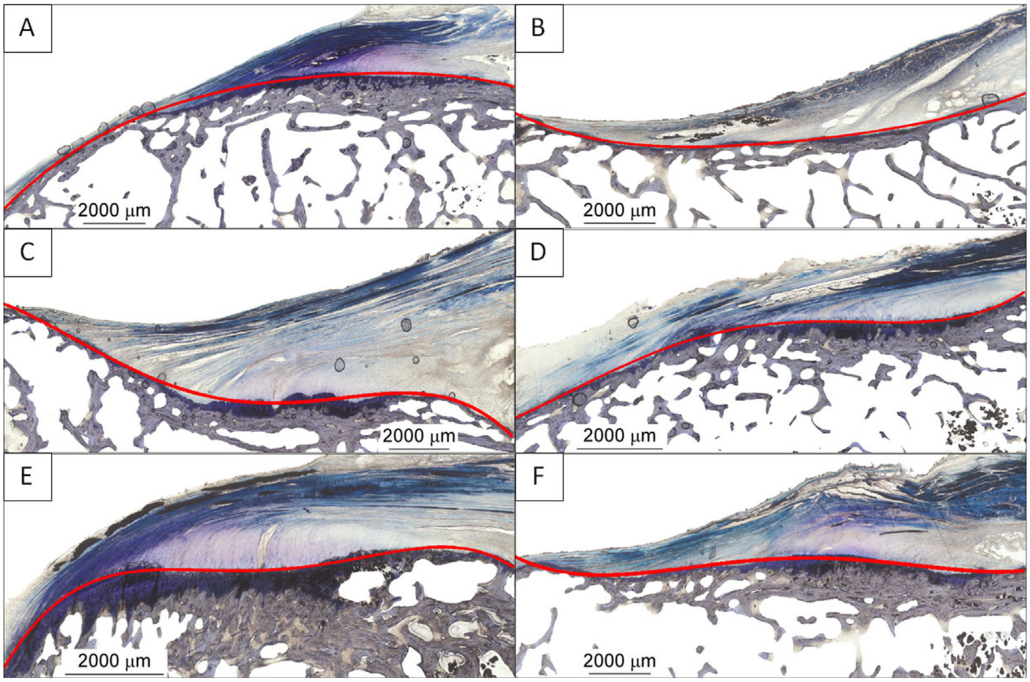

Fig. 1. Human ACL femoral entheseal profile categories include second order convex (A), second order concave (B), third order convex (C), third order concave (D), fourth order convex (E) and fourth order concave (F) polynomial fits. Note that the shapes are classified as convex or concave with respect to the bone in the distal half. In each panel, the proximal end of the enthesis is shown at left, while the distal end is shown at right. Reproduced from Fig. 3 in Beaulieu et al. (2016), used under CC BY 4.0. Lower two rows of panels have been exchanged.

angle than their female counterparts; the average male attachment angle was roughly 13° while the average female attachment angle was just 7°. At the present time, the extent to which the femoral entheseal shape and attachment angle affect ACL stress and strain concentration are unknown.

Therefore, the goals of this study were: (1) to use data from the histological studies performed by Beaulieu and colleagues to inform the development of biomechanical models of the ACL femoral attachment, and (2) to examine the differences in strain distribution among the characteristic tidemark profiles in order to determine whether particular profiles may be more prone to injury than others. A simplified 2D analytical model was constructed, followed by a 3D finite model with similar geometry. Three constitutive models were fit to longitudinal and transverse tensile test data from the literature. Results from all models suggest that a concave enthesis and smaller (more acute) attachment angle increase the strain concentration near the distal edge of the femoral ACL attachment, increasing injury risk. Additional analysis demonstrates that the macroscopic force-extension relationship of the structure is dependent both on the enthesis geometry as well as the constitutive form.

2. Methods

2.1. Analytical model formulation

The ACL femoral enthesis was first modeled as a 2D trapezoidal body of width w rigidly attached to a fixed curve, $y = A(x)$. This curve characterized the entheseal shape at the junction of the calcified and uncalcified fibrocartilage, and it had a mean slope of a/w, such that the insertion angle of the enthesis (ϕ) was 13° or 7°, the average attachment angle for males and females, respectively. Entheseal profiles were constructed from histological slices following the grouping scheme shown in Fig. 1. The opposite edge of the body ($y = L$) represented the ligament proper, which was assumed to undergo a uniform displacement δ. Fig. 2 depicts the variables used in creating the model.

Assuming homogeneity and no Poisson effect, the displacement field in the ligament can be approximated by

$$u_y(x, y) = \frac{\delta}{L - A(x)}(y - A(x)). \quad (1)$$

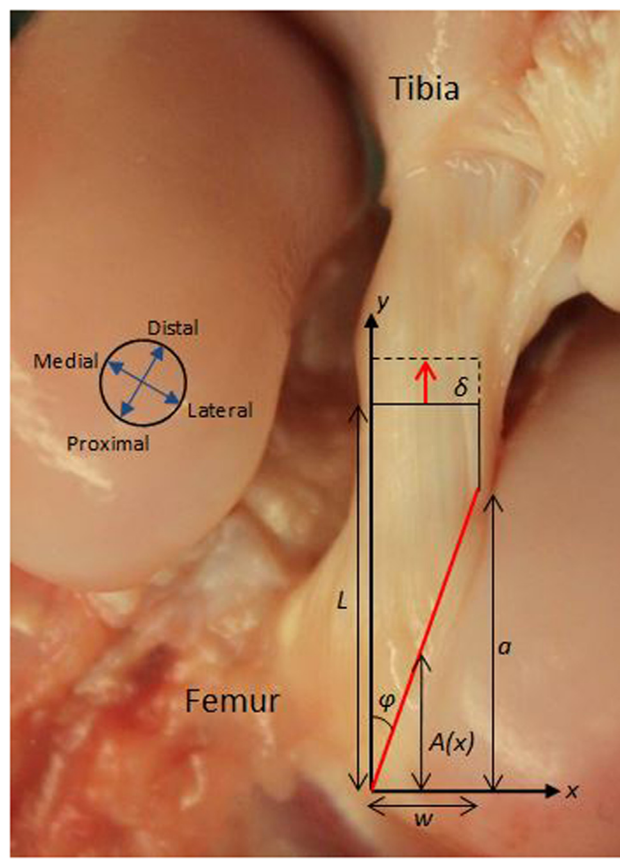

Fig. 2. Diagram depicting the relationships among variables used in the 2D model over an image of an ovine ACL. The red arrow indicates the direction of the displacement (δ) of the boundary $y = L$, which was 10% of L. The red line represents $A(x)$, the femoral enthesis boundary, described by polynomials. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)