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Comparison of elastic, viscoelastic and failure tensile material properties of knee ligaments and patellar tendon

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ABSTRACT

The knee ligaments and patellar tendon function in concert with each other and other joint tissues, and are adapted to their specific physiological function via geometry and material properties. However, it is not well known how the viscoelastic and quasi-static material properties compare between the ligaments. The purpose of this study was to characterize and compare these material properties between the knee ligaments and patellar tendon.

Dumbbell-shaped tensile test samples were cut from bovine knee ligaments (ACL, LCL, MCL, PCL) and patellar tendon (PT) and subjected to tensile testing (n = 10 per ligament type). A sinusoidal loading test was performed at 8% strain with 0.5% strain amplitude using 0.1, 0.5 and 1 Hz frequencies. Subsequently, an ultimate tensile test was performed to investigate the stress-strain characteristics.

At 0.1 Hz, the phase difference between stress and strain was higher in LCL compared with ACL, PCL and PT ($p < 0.05$), and at 0.5 Hz that was higher in LCL compared with all other ligaments and PT ($p < 0.05$). PT had the longest toe-region strain ($p < 0.05$ compared with PCL and MCL) and MCL had the highest linear and strain-dependent modulus, and toughness ($p < 0.05$ compared with ACL, LCL and PT).

The results indicate that LCL is more viscous than other ligaments at low-frequency loads. MCL was the stiffest and toughest, and its modulus increased most steeply at the toe-region, possibly implying a greater amount of collagen. This study improves the knowledge about elastic, viscoelastic and failure properties of the knee ligaments and PT.

1. Introduction

Ligaments are soft tissues in the musculoskeletal system that connect bone to bone. Their main functions are to transmit forces, restrict and guide joint movement, stabilize joints and act as mechanical dampers (Birch, 2013; Reynolds et al., 2017). In the knee joint, they function in concert with each other and other joint tissues, such as articular cartilage and meniscus (Butler et al., 1980; Ellis and Weiss, 2015). They are composed mainly of water (65–70% of total weight), type I collagen (70–80% of dry weight), elastin (few percent), and proteoglycans (few percent) (Woo et al., 2005, 1999). Similar to tendons, ligaments exhibit a hierarchical structure with highly oriented fascicles, formed from fibers, and lower levels of hierarchy at fibril and collagen molecule scale (Ellis and Weiss, 2015).

Adequate mechanical properties of ligaments are essential for the physiological function of the knee joint. Ligaments function primarily in tension in the direction of the collagen fibers and thus tensile properties in that direction are of special interest. Shear, transverse and compressive loads also exist in ligaments (Ellis and Weiss, 2015; Gardiner et al., 2001), but they are less significant during normal joint function. Different ligaments are adapted to their specific function via their geometry and material properties (Birch, 2013). However, time-dependent and failure properties of ligaments at the mesoscopic level are not well known. These properties, such as the Young's modulus and ultimate strength, represent the intrinsic material properties, as opposed to the structural properties of the entire ligaments, and are essential in understanding the structure-function relationships.

During normal locomotion, ligaments and tendons experience dynamic loads. The resulting response of these tissues is time-dependent and affected by their viscoelastic properties. However, studies comparing time-dependent properties of different ligaments have been concentrating on varying strain rates in ultimate tensile testing (Pioletti et al., 1999; van Dommelen et al., 2005), although a sinusoidal test mimics better normal knee function and repeated ligament loading. Sinusoidal test results have been previously reported for human medial collateral ligament

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(Bonifasi-Lista et al., 2005; Lujan et al., 2009), and, to our knowledge, there are no studies which compare the sinusoidal test results of anterior cruciate ligament (ACL), posterior cruciate ligament (PCL), medial collateral ligament (MCL), lateral collateral ligament (LCL) and patellar tendon (PT) from the same set of skeletally mature knees.

Only a few studies have compared stress-strain characteristics of knee ligaments within the same set of knees. Eleswarapu et al. (2011) compared the Young's modulus and ultimate strength of immature (one-week-old) bovine ligaments and found that PT had the highest modulus and strength (27.5 ± 2.8 and 15.7 ± 3.3 MPa), while ACL had the lowest values (2.1 ± 1.0 and 1.4 ± 0.6 MPa), but the low absolute values clearly show the immaturity of the tissues. Butler et al. (1986) compared bone-fascicle-bone units of ACL, PCL, LCL and PT (MCL not compared) of three cadavers, and discovered that ACL, PCL and LCL had no significant differences in the Young's modulus, strength or toughness, while PT had significantly higher values in all those parameters. They observed similar failure strains for ligaments and PT; uniform failure strains have also been suggested for different tendons (LaCroix et al., 2013). Smeets et al. (2017) compared MCL and LCL and observed significantly higher Young's modulus for MCL, and significantly higher failure strain and toughness for LCL. To our knowledge, there are no studies to compare the linear, non-linear and failure material properties of ACL, PCL, MCL, LCL and PT from the same set of skeletally mature knees.

The purpose of the study was to comprehensively characterize and compare the viscoelastic and quasi-static tensile material properties of knee joint ligaments and patellar tendon at the mesoscopic level. Tensile properties were determined experimentally using a sinusoidal loading test and ultimate test until tissue failure using dumbbell-shaped samples of bovine ligaments. In the absence of previous comparative studies of ligament viscoelasticity, but significantly lower water content observed in PT compared to knee ligaments (Rumian et al., 2007), we hypothesized that viscous properties are similar between the ligaments, but lower in PT. Regarding stress-strain characteristics, we hypothesized that collateral ligaments and patellar tendon exhibit higher linear and strain-dependent Young's modulus than cruciate ligaments (Butler et al., 1986; Eleswarapu et al., 2011; Smeets et al., 2017), while toe, yield and failure strains are similar between ligaments (Butler et al., 1986; LaCroix et al., 2013). The results of this study aid in understanding the differences in the elastic and viscoelastic material properties of knee joint ligaments and PT, and their structure-function relationships.

2. Methods

2.1. Sample preparation

Anterior cruciate ligament (ACL), posterior cruciate ligament (PCL), medial collateral ligament (MCL), lateral collateral ligament (LCL) and patellar tendon (PT) were carefully dissected from 10 skeletally mature bovine stifle joints. The measurements were conducted using dumbbell-shaped samples, approximately 10 mm in length and 1.8 and 2 mm in thickness and width (Fig. 1a and b) (Bonifasi-Lista et al., 2005; Chokhandre et al., 2015; Eleswarapu et al., 2011; Henninger et al., 2013; Quapp and Weiss, 1998; Stabile et al., 2004). Detailed information on sample preparation can be found in the supplementary material.

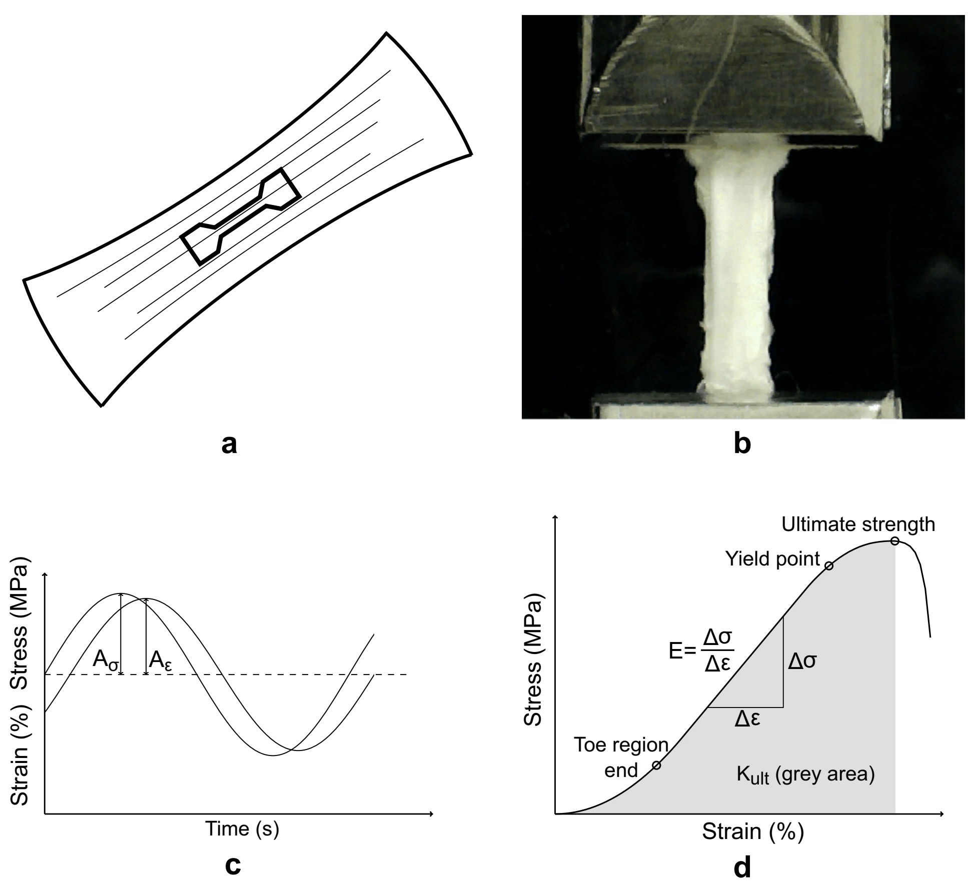

Fig. 1. A dumbbell-shaped tensile test sample was cut from the central part of the ligament (a) and then subjected to tensile testing (b). Schematic presentation for sinusoidal (c) and ultimate testing (d) with certain analyzed parameters indicated.