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# Mechanical Analysis of Extra-Articular Knee Ligaments. Part One: Native knee ligaments

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A B S T R A C T

*Background:* The aim of this study was to provide a characterization of the tensile properties of the medial collateral ligament (MCL), lateral collateral ligament (LCL), anterolateral ligament (ALL) and medial patellofemoral ligament (MPFL). Our hypothesis was that extra-articular knee ligaments are heterogeneous in nature and possess distinct material properties.
*Methods:* MCL (n = 12), LCL (n = 11), MPFL (n = 12) and ALL (n = 19) samples from fresh frozen human cadaveric knees were subjected to uniaxial tensile testing to failure and analyzed for their material properties. The elastic modulus (slope of the linear portion of the stress/strain curve), ultimate stress (stress at failure), ultimate strain (strain at failure) and strain energy density (area under the stress/strain curve) were calculated.
*Results:* The MCL had the highest elastic modulus (441.8 ± 117.2 MPa) and was significantly greater than the MPFL (294.6 ± 190.4 MPa) and LCL (289.0 ± 159.7 MPa) ($P < 0.05$) as well as the ALL (173.7 ± 91.8 MPa) ($P < 0.001$). The ultimate stress was significantly higher ($P < 0.05$) for the LCL (83.6 ± 38.1 MPa) and MCL (72.4 ± 20.7 MPa), relative to the MPFL (49.1 ± 31.0 MPa) and ALL (46.4 ± 20.1 MPa). The ultimate strain of the LCL (41.0 ± 9.9%) and ALL (37.8 ± 7.9%) were significantly higher ($P < 0.05$) compared to the MCL (22.9 ± 2.5%) and MPFL (22.2 ± 5.6%). The strain energy density of the LCL (15.2 ± 6.4 MPa) was significantly greater ($P < 0.05$) than all other ligaments (ALL 7.8 ± 3.1 MPa, MCL 7.5 ± 2.9 MPa and MPFL 5.0 ± 2.9 MPa).
*Conclusions:* Extra-articular knee ligaments are a heterogeneous group with respect to material characteristics. Each ligament has tensile properties that are significantly different from others and treatment strategies should take these findings into account.


## 1. Introduction

Injuries to knee ligaments are very common, particularly in sports-related activities [1], with an estimated rate of occurrence in the general population approaching 2/1000 people per year [2]. Ruptures of these ligaments can result in chronic instability and

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secondary damage to other structures, such as the cartilage and meniscus. Surgical treatment often involves reconstruction with auto- or allografts [3–16] and therefore, knowledge of the mechanical properties of ligaments is essential to elucidate their in vivo behavior and function, as well as for selecting appropriate grafting materials used in reconstruction procedures.

The intrinsic mechanical properties of a ligament depend upon several factors including collagen composition, fiber orientation, and the interaction between collagen and ground substance [17]. A wide variation of grafting materials and surgical techniques are used for the reconstruction of extra-articular ligaments such as the medial collateral (MCL) [3–5], lateral collateral (LCL) [6–9], medial patellofemoral (MPF) [10–12], and anterolateral (ALL) ligaments [13–16]. Despite this, there are only a few studies investigating the intrinsic mechanical behavior of human extra-articular knee ligaments, and many previous studies have only characterized the structural properties of bone–ligament–bone complexes [18–20]. Moreover, an advantage of this study is that ligaments of the same cadaveric specimen are tested using an identical testing method.

In current clinical practice, graft materials are often chosen because of their size, structural properties, ease for harvesting, and availability [3,6,7,21–23]. To enhance the effectiveness of various treatment procedures and to deal with problems such as over-constraining versus residual joint laxity, it is essential to know the intrinsic characteristics of ligaments in order to mimic them with the appropriate graft. Therefore, the primary objective of this work is to provide a detailed characterization of the tensile properties of the MCL, LCL, ALL, and medial patellofemoral ligament (MPFL). We hypothesize that extra-articular ligaments are heterogeneous in nature and possess distinct material properties.

## 2. Methods

Twelve fresh-frozen full-body cadavers (74 ± 7 years, 10 men, two women) were obtained under ethical approval from the Institutional Review Board at KULeuven. No donor had a history of knee injury, instability, or prior surgical intervention. Additionally, three knees were excluded because of grades III and IV arthrosis or ACL deficiency. From 12 of the 21 specimens, the ALL, superficial MCL, LCL, and MPFL were dissected using previously described techniques [24,25]. Nine knee specimens were only dissected for the ALL and could not be used for harvesting other ligaments because of other research purposes. Consequently, a total of 21 ALL, 12 MCL, 12 LCL, and 12 MPFL samples were taken by the same orthopedic resident (KS). Once removed, the samples were wrapped in saline-soaked gauze, placed in freezer bags, and stored at −80 °C until the time of testing.

### *2.1. Mechanical testing*

Prior to testing, samples were removed from the freezer and allowed to thaw at room temperature for 24 h. Once thawed, samples were cut into standardized shapes (dog-bone) using a surgical scalpel to form a uniform cross-sectional area in the mid-substance of the tendon, thus providing a uniform stress distribution during testing [26,27]. Samples were mounted in custom-made tensile grips which had sandpaper between the grip faces to provide anchorage. Additionally, cyanoacrylate adhesive

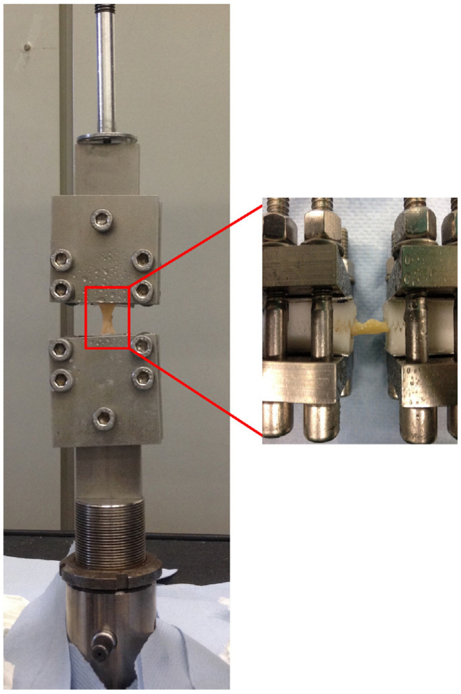

**Figure 1.** The clamping system used to perform tensile testing of the tissue specimen.

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