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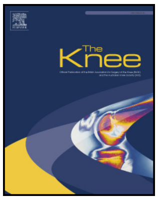

Mechanical Analysis of Extra-Articular Knee Ligaments. Part two: Tendon grafts used for knee ligament reconstruction

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ABSTRACT

Objectives: The aim of this study was to provide information about the mechanical properties of grafts used for knee ligament reconstructions and to compare those results with the mechanical properties of native knee ligaments.
Methods: Eleven cadaveric knees were dissected for the semitendinosus, gracilis, iliotibial band (ITB), quadriceps and patellar tendon. Uniaxial testing to failure was performed using a standardized method and mechanical properties (elastic modulus, ultimate stress, ultimate strain, strain energy density) were determined.
Results: The elastic modulus of the gracilis tendon (1458 ± 476 MPa) ($P < 0.001$) and the semitendinosus tendon (1036 ± 312 MPa) ($P < 0.05$) was significantly higher than the ITB (610 ± 171 MPa), quadriceps tendon (568 ± 194 MPa), and patellar tendon (417 ± 107 MPa). In addition, the ultimate stress of the hamstring tendons (gracilis 155.0 ± 30.7 MPa and semitendinosus 120.1 ± 30.0 MPa) was significantly higher ($P < 0.001$, respectively $P < 0.05$), relative to the ITB (75.0 ± 11.8 MPa), quadriceps tendon (81.0 ± 27.6 MPa), and patellar tendon (76.2 ± 25.1 MPa). A significant difference ($P < 0.05$) could be noticed between the ultimate strain of the patellar tendon (24.6 ± 5.9%) and the hamstrings (gracilis 14.5 ± 3.1% and semitendinosus 17.0 ± 4.0%). No significant difference in strain energy density between the grafts was observed.
Conclusions: Material properties of common grafts used for knee ligament reconstructions often differ significantly from the original knee ligament which the graft is supposed to emulate.

1. Introduction

The use of tendon autografts for knee ligament reconstructions is extremely common. Different grafts around the knee have been used for intra- and extra-articular ligament reconstructions. Many graft materials show good clinical results and are chosen because of

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their size, structural properties, ease of harvesting, patient activity level, surgeon experience and preference, and availability [1–7]. Hamstring autografts are often preferred as grafts because of their low donor-site morbidity [8], tensile strength [7] and their geometric properties [1]. For anterior cruciate ligament (ACL) reconstructions, the patellar tendon autograft is a widely accepted graft with good to excellent clinical results [8,9]. On the other hand, the quadriceps tendon is less commonly used for this, but also has been reported with excellent results with a low rate of morbidity [10]. Finally, the use of the iliotibial band (ITB) as a graft is particularly popularized for a lateral extra-articular tenodesis in combination with ACL reconstructions to better control knee rotation [11–13].

Too stiff grafts have the potential to overconstrain a certain part of the joint thus theoretically predisposing the patient to detrimental long-term effects on the cartilage [14]. On the other hand, more elastic grafts can cause residual joint laxity. Knowledge about the mechanical properties is therefore important for understanding the intrinsic behavior of the graft itself and is necessary information for choosing a graft and for comparing it with the native ligament. Those properties are independent of the size or amount of tissue and are not influenced by the effect of the attachment sites [15].

While the mechanical properties of the patellar tendon are well established [16–27], there are relatively few studies on the hamstrings [16,17,23,28], ITB [16,17,29], and quadriceps tendon [17,24,25,30]. Moreover, between those studies, much variation in results is observed and comparing such studies is difficult because results can vary markedly depending on the methods of testing and the biologic variability that exists between human cadavers [7]. Therefore, the primary purpose of this study was to provide information about the mechanical properties of typical grafts currently used for knee ligament reconstructions. We hypothesize that those grafts present different mechanical characteristics. The secondary purpose was to compare those results with the previously studied mechanical properties of native knee ligaments [31]. The hypothesis was that the mechanical properties of knee ligaments are distinct from the tendon grafts used to reconstruct them.

2. Methods

Eleven cadaver knees (82 ± 24 years) were obtained under ethical approval from Katholieke Universiteit Leuven. The knees had no history of injury, instability, or prior surgical intervention. Additionally, donors with grade III or IV arthrosis or ACL deficiency were excluded. For graft harvesting, a midline incision was performed. The hamstring tendons (gracilis and semitendinosus) were identified under the sartorius aponeurosis and were cut at their tibial insertion. With a closed stripper, they were detached from their muscle bodies and examined to ensure that there were no signs of damage. The middle third of the patellar tendon was cut from the insertion sites on the patella and tibial tubercle. The quadriceps tendon sample was taken by making a 10-cm-long and two-centimeter-wide partial thickness strip and peel it off from the patella insertion. Furthermore, a 10-cm-long and two-centimeter-wide-wide ITB strip was cut out and detached from the periosteum at Gerdy's tubercle. In total, 11 samples from each graft were dissected from the specimens by the same orthopedic resident. 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 [32,33]. Samples were mounted in custom-made tensile grips that had sandpaper between the grip faces to provide anchorage. Additionally, cyanoacrylate adhesive was used to provide additional protection against slippage. The tensile grips were aligned axially (i.e. in line with the ligament fibers) within a materials testing frame (model 4467, Instron, Norwood MA, USA) equipped with a one-kilonewton calibrated load cell (Figure 1). A one-newton preload was applied to the samples and measurements of the cross-sectional area were taken with a digital micrometer five times and the average calculated, always by the same researcher. The distance between the grip faces was measured and was used as the original gage length. Ten preloading cycles consisting of a ramp from one to 10 N at a strain rate of $0.1\%s^{-1}$ were performed which were followed immediately by a ramp-to-failure test at a strain rate of $2\%s^{-1}$. Force and displacement data were measured at 100 Hz. Samples were kept wet with saline to prevent dehydration and all tests were performed at room temperature (~22 °C).

Only those samples that showed mid-substance failure were used. Consequently, data from 11 semitendinosus, 11 gracilis, nine ITB, nine quadriceps, and eight patellar tendons were analyzed. The collected force and displacement data were converted to stress (applied force/average cross-sectional area) and strain (change in length/original gage length) to allow the calculation of the ligament mechanical properties: 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 (energy absorbed to yield).

2.2. Statistical analysis

Commercially available software (SPSS 24, IBM, Armonk, NY, USA) was used for all statistical analysis and the significance level was set to $\alpha = 0.05$. Data were found to exhibit normal distributions using the Shapiro–Wilk test, therefore, parametric statistical analysis was used. Data were assessed for significance using one-way analysis of variance (ANOVA) with pairwise multiple comparisons used for post hoc analysis (corrected for multiple comparisons with the Bonferroni adjustment). Additionally, the homogeneity of variance was assessed using Levene's test. If data were found to violate the (ANOVA) assumption of homogeneity, the Brown–Forsythe test was utilized. Where applicable, data are presented as the mean ± standard deviation.

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