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Effects of cyclic loading on the tensile properties of human patellar tendon

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ABSTRACT

Bone–patellar tendon-bone (BPTB) graft is a popular choice for ACL reconstruction. These grafts are subjected to cyclic loading during the activities of daily living. Significant knee laxity is observed in reconstructed knee shortly after reconstruction. The source of this laxity is not clear. The change in the tensile properties of the graft due to cyclic loading can be one of the reasons for the change in knee laxity.

Twenty patellar tendons from fresh frozen cadaver knees were cyclically loaded at a stress amplitude equivalent to 33% of the failure strength of the contralateral patellar tendon for 5000 cycles at 1.4 Hz. They were then tested in tension to failure. Failure properties and the low load properties such as toe-region modulus were calculated. The results were compared with those of contralateral patellar tendons that were not subjected to cyclic loading before testing to failure.

Fatigue loading did not alter the failure and low load properties with the exception of failure strain which decreased by about 10% ($P<.05$). Cyclically loaded patellar tendons with higher tissue mass density possess higher strength, modulus of elasticity, toughness, and transition stress ($P<.05$). The results indicate that there is no significant change in graft properties because of cyclic loading with the above load magnitude. The change in knee laxity observed after reconstruction, hence, is not because of change in graft properties due to moderate cyclic loading. Other factors, such as plastic deformation (yielding) of the graft, might play a role in increased knee laxity after reconstruction.

1. Introduction

The most commonly used graft material for ACL reconstruction is bone–patellar tendon–bone (BPTB) complex. While several other factors such as surgical technique, fixation method and rehabilitation protocols might affect the post operative knee laxity and subsequent development of osteoarthritis, the mechanical behaviour of the graft material is also an important factor. The load-deformation or stress–strain curve obtained from tensile tests is often used to assess the mechanical behaviour of patellar tendons. These curves have an initial non-linear region called a toe-region and a later linear region called linear-elastic region. The properties of the material in the toe-region (often referred to as low-load properties) are as important as the linear elastic region properties and the failure properties [1].

While some pretension is applied to the BPTB graft during reconstruction, it is evident that the graft loses some of its pretension immediately after the reconstruction resulting in higher knee laxity [2]. A recent cadaveric study reported that the BPTB graft loses its initial tension by 41% at the end of 1500 flexion–extension cycles [3]. Such loosening of the graft results in increased knee laxity and could lead to osteoarthritis. The reasons as to why the knee becomes laxer after several cycles of flexion and extension are not clear. The change in low load and elastic region properties of the graft due to cyclic loading may be one of the reasons.

Ligaments are cyclically loaded during activities of daily living. These loads are generally low during activities such as walking and stair climbing resulting in peak ligament strain values of less than 4% [4]. This corresponds to about 25% of the ultimate strain of BPTB graft [5]. Noyes et al. state that between 25%–50% of the ultimate tensile force is applied to the ligaments during normal to strenuous activity [6]. Activities such as jogging and running can be considered moderate and could result in about 35% of the ultimate load of the BPTB graft. The effects of cyclic loading on the low-load and failure properties of the BPTB are thus very important. However, most of the biomechanical studies on the BPTB consist of stretching the tissue to failure [7–9]. Sometimes they are cyclically loaded only for few cycles at very low load levels for the purpose of preconditioning. One study reported the effect of cyclic stretching on failure properties of human patellar tendons [10]. They cycled the patellar tendons to approximately 25% of the failure deformation (2.5 mm) for 20 cycles before stretching it to failure. They reported that cyclic stretching did not alter the failure properties of patellar tendons. The number of cycles the tissue was cycled was low in this study compared with Berkson et

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al. who compared the effects of cyclic loading on twisted and untwisted porcine patellar tendons for cycling them for 5000 cycles [11]. They found that twisting the patellar tendons does not affect their failure properties. The focus of this study was to study the effects of twisting, not to study the effects of cycling.

None of the reported studies deal with the effects of moderate level cyclic loading on the failure properties of human patellar tendons. Furthermore, the studies do not address toe-region properties that are also very important properties that define the behaviour of the graft during activities of daily living [1]. In this study we investigate the effects of extensive moderate amplitude cyclic loading on the low-load, linear-elastic and failure properties of human patellar tendon. Unless the effects of cyclic loading on the low-load, linear elastic and failure properties of patellar tendon are investigated, the reasons for knee laxity after ACL reconstruction cannot be understood. We hypothesized that extensive cyclic loading up to 33% of the BPTB graft failure strength (determined by the testing to failure of the graft in the contra lateral knee) will not significantly alter either the toe-region, linear-elastic or failure properties of the tissue.

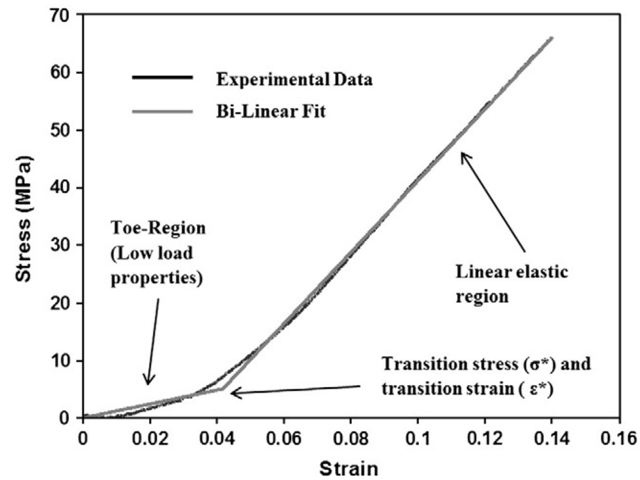

Fig. 1. The bilinear fit for the stress–strain curve distinguishing the linear region and toe-region properties.

2. Methods

The study design we used is a descriptive experimental study using cadaver knee specimen harvested from body donors. Twenty BPTB grafts (10 male and 10 female) were harvested from fresh frozen cadaver knees. All the grafts were from healthy knees with an age range of 17–50 years. These knees were contralateral knees used in our previous studies in which we studied the mechanical properties of BPTB grafts without subjecting them to cyclic loading [1,5]. The central portion of the patellar tendon (about 4.5 mm) was trimmed. This would result in more uniformly loaded fibers during tensile testing and would prevent insertion site failures [12]. The specimen dimensions were measured using a digital calliper. The bone plugs of the BPTB graft were potted in a custom-made jig and mounted on a tensile testing apparatus (Model 8500+, Instron, MA, USA). The specimen were cycled for 5000 cycles at 1.4 Hz (the frequency at which it would be loaded in normal walking [13]) and then loaded to failure at a strain rate of 100%/s along its longitudinal axis. The minimum load of a cycle was always 25 N while the maximum load was adjusted so that it resulted in 33% of the failure stress of the contralateral patellar tendon [5]. During testing the specimens were regularly sprayed with saline solution to maintain hydration. The load and elongation data were collected from the tensile testing apparatus. The patellar tendon was then separated carefully using a scalpel and weighed in a digital balance (0.001 g accuracy). The mechanical properties and the mass density of the tissue were calculated from the collected data.

The stress–strain curve was then divided into toe region and linear elastic region by fitting the portion of the stress–strain curve that includes the toe region and the corresponding transition to the linear region, to the following bilinear constitutive model

$$\begin{aligned}\sigma &= E_0\varepsilon \text{ where } \varepsilon \le \varepsilon^* \\ \sigma &= E(\varepsilon - \varepsilon^*) + E_0\varepsilon^* \text{ where } \varepsilon > \varepsilon^*\end{aligned} \quad (1)$$

where σ is the engineering stress, ε is the engineering strain, ε^* is the strain at the transition point between the toe-region and linear regions (transition strain), E_0 is the modulus of elasticity of the toe-region and E is the modulus of elasticity of the linear region (Fig. 1).

Analysis of covariance (ANCOVA [14]) was used to test the significance of the effects of donor factors such as age, body mass, body mass index (BMI), height, sex and tissue density on the tissue properties such as toe region modulus, transition stress, linear region modulus, failure stress, failure strain and toughness. Paired t-test, between the cycled tissues in the present study and uncycled tissues in the previous study [5], was used to compare the effect of cycling on these properties. This eliminates any effects of donor factors masking the effects of cyclic stretching. The level of statistical significance (alpha) for all the statistical tests was set to 0.05 a priori.

3. Results

The average and standard deviation of the toe-region and linear properties of the non-cycled/tested-to-failure and cycled/tested-to-failure grafts and their respective P-values based on paired t-test are presented in Table 1 (linear properties) and Table 2 (toe-region properties). The only significant difference in the toe region and linear properties between the two populations was the strain at failure.

Paired t-tests did not show any evidence of significant differences in ultimate strength, modulus of elasticity, toughness, toe region modulus, transition strain and transition stress, before and after cycling when the sexes were analyzed separately or in the pooled population. Only ultimate strain was significantly greater in the non-cycled group when compared to the cycled group when the populations were pooled.

The ANCOVA revealed that no evidence of any of the donor factors significantly affecting the failure strain in cyclically loaded tissues. In contrast, in the tissues that were not cyclically loaded [1] ultimate strain was affected by body mass, height and BMI. Body mass and tissue density significantly affected the ultimate stress. In the current study, the denser the tissue and the heavier the donor was, stronger was the tissue after cyclical loading. This is similar to the results observed in tissues that were not cyclically loaded. The modulus of elasticity was affected by tissue density and BMI in cyclically loaded tissues. Tissue density was the only significant covariate for modulus of elasticity in the case of tissues that were not cyclically loaded. Toughness was influenced by tissue density and body mass in cyclically loaded tissues. In tissues that were not loaded cyclically, body mass, BMI and tissue density were significant covariates for toughness.

As far as low-load properties are concerned, there was no evidence of any of the donor factors significantly affecting the toe region modulus. This is in contrast with sex and height being significant donor factors for the toe region modulus when the grafts were not cycled [1]. BMI had a significant effect on the transition strain in the cyclically loaded tissues. In non-cyclically loaded tissues, none of the covariates were significant. Density was the only significant covariate with respect to transition stress in cyclically loaded tissues. In non-cyclically loaded tissues several donor factors (BMI, body mass, height and sex) were significant covariates.

Table 1
Comparison of linear properties between cycled and non-cycled grafts. Failure strain ε, failure stress σ, linear modulus E and the toughness u were compared.

		ε	σ (MPa)	E (MPa)	u (MPa)
Non-cycled-tensile tested	Mean	0.18	59.2	513.9	4.6
	Std. dev.	0.04	16.5	136.4	1
Cycled- tensile tested	Mean	0.16	61.4	565.3	4.5
	Std. dev.	0.03	20.2	180.2	1.9
	P-value (power)	0.04 (54%)	0.4 (13%)	0.1 (38%)	0.5 (10%)
	Percent difference	11%	3.70%	10%	2.20%