

The mechanical properties of the human patellar tendon are correlated to its mass density and are independent of sex

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Abstract

Background. A diverse range of values for the mechanical properties of the human patellar tendon has been reported in the literature. Donor age has been excluded as a factor that causes this disparity. However, the effects of donor sex and tissue mass density on the mechanical properties of the patellar tendon have not been established. More importantly, predictors of the mechanical properties of the patellar tendon, used as grafts in anterior cruciate ligament reconstruction surgeries, are not available.

Methods. Uniaxial tension tests were performed to determine the effects of donor sex and mass density of the tissue on the mechanical properties of twenty unpaired human patellar tendons (10 male and 10 female; age, 17–50). Mass density of the patellar tendon was determined by measuring its volume and mass.

Findings. No evidence of sex-based differences in any of the mechanical properties of the patellar tendon was found. The results revealed a diverse range of mass densities extending from a low of 0.76 g/cm³ to a high of 2.68 g/cm³ (250% difference). Furthermore, it was determined that the ultimate tensile strength (mean = 58.71 MPa), elastic modulus (mean = 507.38 MPa) and strain energy density (mean = 4.59 MPa) of the patellar tendon were significantly correlated to its mass density. The tensile strength and elastic modulus were significantly higher for those patellar tendons having a mass density greater than 1.67 g/cm³.

Interpretation. The mass density of the patellar tendon may be considered as an indicator of mechanical properties of the patellar tendon or graft quality.

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Keywords: Patellar tendon; Mass density; Graft quality; Sex; Mechanical properties

1. Introduction

The mechanical behavior of the patellar tendon has been studied extensively, and a range of values for properties such as tensile strength, modulus of elasticity, failure strain, and strain energy density at failure have been reported. For instance, tensile strength values ranging from 26.6 MPa to 95.5 MPa have been published (Haut and Powlison, 1990; Cooper et al., 1993); the reported modulus of elasticity ranges from 191 MPa to 660

MPa (Haut and Powlison, 1990; Johnson et al., 1994); and failure strain percentages vary from 13.5% to 31.4% (Butler et al., 1986; Flahiff et al., 1994). It is evident that there is some inconsistency in the reported mechanical properties. Since age is known to have little effect on the mechanical properties of the patellar tendon, at least in the age range of below 50 years, (Blevins et al., 1994; Flahiff et al., 1994), there may be other variables that affect the mechanical behavior of the patellar tendon. Although test environment (Haut and Powlison, 1990) and specimen cross-sectional area (Atkinson et al., 1999) are known to affect the results, some published results that have used similar test environments and

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specimen cross-sectional area (Butler et al., 1986; Cooper et al., 1993; Blevins et al., 1994; Flahiff et al., 1994) still report considerably different values for various mechanical properties. A summary of the reported values and some critical test variables including sample size, donor-age range, and test environment are presented in Table 1. A careful review of this table shows that variables other than the test environment, treatment and specimen cross-sectional area, may influence the mechanical properties of the patellar tendon.

The reconstruction of the ruptured anterior cruciate ligament (ACL) through the utilization of graft materials is a routine surgical procedure. The patellar tendon has become the most popular graft material for ACL reconstruction since its introduction by Jones (1963). The ease with which the graft can be set in the bone tunnel and its high strength are the main reasons for its popularity in ACL reconstruction surgeries. Both allografts and autografts of patellar tendons are regularly used for ACL reconstruction. Recent studies have shown that close to 8% of the patients experience graft failure after the primary surgery (Noyes and Barber-Westin, 1997) when the reconstruction was carried out using autogenous patellar tendon grafts. Another study (Beynon et al., 2001) reported that those autografts showing less stiffness, immediately after surgery, resulted in excessive knee laxity after several years. One factor that could cause the reported problems may be related to the variability in the mechanical properties of the graft material. In other words, since no predictors of the quality of the grafts exist, low quality grafts may unknowingly be used for reconstruction. Thus, the knowledge of the behavior and properties of the patellar tendon, and the variables that affect its mechanical properties, prior to surgery, are of clinical importance for the long-term health and activity of the patient.

There is evidence in the literature that the mechanical properties of some connective tissues vary between males and females. Sex hormones, such as estrogen, are also reported to affect the mechanical properties of

connective tissues. Kubo et al. (2002) reported that female tendon structures of the medial gastrocnemius muscle has a lower elastic modulus. Slauterbeck et al. (1999) reported that estrogen reduces the failure load of the rabbit ACL. However, Rasanen and Messner (2000) reported that estrogen increased the ultimate strength of the rabbit medial collateral ligament (MCL). Sex has not been investigated as a potential factor contributing to the existing range of values and mechanical properties of the patellar tendon. Importantly, a recent report has shown that a sex-based difference in the tear rate of reconstructed ACLs does not exist, when reconstruction is carried out with autogenous patellar tendons of uniform size (Shelbourne et al., 1998). The above study might point toward an absence of a sex-based difference in the failure strength of patellar tendons. However, absence of injury, by itself, does not verify the absence of sex-based differences in mechanical properties. Other properties such as elastic modulus and toughness, which might not directly contribute to injury, may still be different between the sexes. Therefore, more direct studies of cadaveric patellar tendons are required to test for possible sex-based differences in the mechanical properties. If such differences were found, it would be worthwhile to consider sex as a variable that contributes to the existing inconsistencies and also a factor that might affect the performance of the graft.

Tendons are made up of collagen fibrils and a gelatinous matrix. From a materials point of view, the ratio between the fibril and matrix, which determines the collagen content of the tendon, may affect the mechanical properties of the tendon. A correlation between collagen content and mechanical properties of tissues has been reported in the literature. In one such study, Haut et al. (1992) reported that the collagen content in the canine patellar tendon positively correlated to the tensile modulus of the tendon. In another study, Woo et al. (1981) reported that exercise increased both tissue mass and collagen content of the swine digital extensor tendon and also increased its tensile strength. Therefore, one

Table 1
Comparison of material properties of the patellar tendon from different sources

	<i>n</i>	Age	Area, mm ² (environment)	σ_u , MPa	<i>E</i> , MPa	ϵ_f (%)	<i>u</i> , MPa
Noyes et al. (1984) ^a and Butler et al. (1984) ^a	7	26 (6)	50.5 (drip)	58.3 (6.1)	305 (59)	26.5 (2.9)	9.9 (1.9)
Butler et al. (1986) ^a	3	21–30	1.6 (bath)	68.5 (6)	643 (53)	13.5 (7)	5.03 (0.07)
Haut and Powlison (1990) ^a	3	20–44	70.3 (drip)	26.6 (2.8)	191 (16)	26.6 (10)	–
Cooper et al. (1993) ^a	5	28 (7)	32.3 (drip)	95.5 (16.8)	–	15.8 (4)	–
Johnson et al. (1994) ^b	15	29–50	14.6 (bath)	64.7 (16)	660 (266)	14 (6)	4.33 (2.5)
Blevins et al. (1994) ^a	82 ^c	17–54	48.4 (drip)	35.9 (10.9)	310 (95)	–	–
Flahiff et al. (1994) ^b	33	18–55	45.0 (drip)	78.4 (18.5)	340 (97)	31.4 (5.9)	–

A wide discrepancy in reported values can be observed.

^a Data given as mean (SEM).

^b Data given as mean (SD).

^c From 25 donors.

can assume that an increase in collagen content, that influences the mechanical properties, can manifest itself in an increase in the mass of the tendon. However, for comparative purposes, mass density of the tendon might be a better indicator of the relative collagen content and therefore the graft quality. Presently, no published study correlates mass density of the patellar tendon in humans with its mechanical properties. If such a correlation exists, it can explain some of the existing variability in the reported data on mechanical properties of the patellar tendon. Furthermore, such correlation can be used to assess the mechanical quality of the autograft prior to the ACL reconstruction. The need for such predictors of quality is suggested by some researchers (Beynnon et al., 2001).

In this study, we hypothesize that (1) female patellar tendons have inherently inferior mechanical properties as compared to male patellar tendons, (2) the mechanical properties of the patellar tendon are correlated to its mass density; and therefore, mass density may be used as a predictor of graft quality.

2. Methods

Twenty unpaired knees (10 male and 10 female) were harvested from 20 donors of Caucasian origin and were frozen at -20°C until the day of the experiment. The knees were frozen within 12 h after death, and the duration each knee was frozen varied from approximately 6 months to 24 months. The cadavers that met any of the following conditions were excluded from this research: (i) over the age of fifty, (ii) skeletally immature (below age of 16 for females and 19 for males), (iii) prior history of knee surgery or (iv) history of osteoarthritis. The age and body anthropometry data of donors were recorded and are given in Table 2. The age range given in Table 2 was selected because the majority of the ACL reconstruction is carried out in patients of this age range.

Before dissection, the knees were thawed at room temperature. The patellar tendon, along with the entire patella and part of the tibial bone, containing the tibial tubercle, was harvested from the knee. The tibial bone was cut in a wedge shape manner. The central portion of the patellar tendon (average width of about 5 mm) was trimmed using a sharp scalpel to maximize intrasubstance failure (Johnson et al., 1994), as shown in Fig. 1. The trimming was performed along the length of the

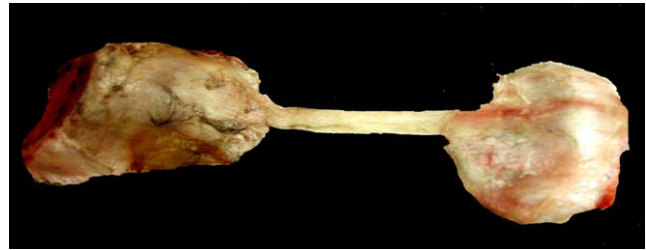


Fig. 1. Central portion patellar tendon (approximately 5 mm wide) used for tensile testing. The shape of the patella and wedge-shaped tibial tubercle prevented slippage during the tensile testing.

bundles, medially and laterally. Care was taken not to disrupt the bundles transverse to the cut.

The length of the patellar tendon as well as its width and thickness were measured along different sections of mid-substance using a caliper and the values were averaged (Haut and Powlison, 1990). It is important to note that since the patellar tendon was shaved along the length of the fascicles, the damage to the tendons was minimal. Furthermore, since the fascicles run straight from bone to bone, the shaved edges are straight and the cross-sectional shape of the tendon is approximately rectangular due to the flat anterior and posterior surfaces. Due to the approximately flat surfaces, the cross-sectional area of the tendon could be measured using a caliper with reasonable accuracy. The cross-sectional area of the trimmed patellar tendon was calculated using the measured width and thickness. The corresponding volume was obtained by multiplying the cross-sectional area by its length. Woo et al. (1990) reported a 2% level of inaccuracy when measuring the dimensions of the rabbit MCL using this technique (compared to laser micrometer technique). Since MCL and patellar tendons are similar in their cross-sectional shape, the error involved in measuring the cross-sectional area in our study is expected to be minimal.

The patella and tibial bone were then potted using a low melting point alloy Cerrobend ($T_{\text{melt}} = 70^{\circ}\text{C}$). Care was taken to assure that the molten alloy did not come in contact with the patellar tendon by wrapping the patellar tendon with saline-soaked gauze. The potted patellar tendon was then mounted on a custom-made jig and fitted to a servo-hydraulic tensile testing machine as shown in Fig. 2. The custom-made jig, with angular and rotary degrees of freedom facilitated the orientation of the patellar tendon parallel to the loading axis so that the fibers

Table 2
Average values of donor age, mass, height and body mass index (BMI)

	Age	Body mass, kg	Height, cm	BMI, kg/m^2
Male	39 (26–50)	78.07 (54–121.5)	177.01 (167.6–182.8)	24.82 (19.2–37.3)
Female	37.7 (17–50)	70.38 (49.5–111.6)	164.4 (152.4–175.2)	26.13 (19.9–44.4)

The range of variables is given in parenthesis.



Fig. 2. BPTB complex mounted on tensile testing machine for tensile testing.

were loaded in their anatomic orientation. Before testing, the specimens were preconditioned by load-controlled cycling between 20 and 100 N for twenty cycles at 0.25 Hz to remove any crimping in the tendon fibrils caused due to prolonged storage in a fixed position.

After preconditioning, the bone-patellar tendon-bone complex was loaded to failure at a strain rate of 100%/s (Noyes et al., 1984). The load and displacement data were collected from the load cell and the actuator displacement at 5 kHz sampling rate using a computerized data acquisition system. After the test, both segments of the failed patellar tendon were carefully removed from their attachment sites using a scalpel and were weighed using a digital scale (accuracy ± 0.001 g). Failure of the tendon was assumed to occur at the point of maximum force on the load–elongation curve. The mechanical properties of the patellar tendons were calculated based on the geometry and the load–elongation data. The elastic modulus was calculated by measuring the slope of the stress–strain curve in its most linear region (usually immediately after the toe region). The toughness (strain energy density) of the tendon, which is a measure of energy absorbed before failure, was calculated by measuring the area under the stress strain curve. The mass density of the patellar tendon was calculated by dividing its mass by its volume. The patellar tendon was kept moist by spraying 0.1 N saline solution throughout the experiment (including the sample preparation and preconditioning stages) using an atomizer.

Based on the reported sex-based difference of 30% in the elastic modulus of the medial gastrocnemius muscle, Kubo et al. (2002), and using the data published by Johnson et al. (1994), a power analysis was performed. It revealed that a sample size of 10 (in each sex) would be sufficient to detect a stress difference of about 18 MPa between sexes at a power of 75%.

Student's *t*-test was performed to compare the mechanical properties of the patellar tendon between the sexes after testing the obtained data for normality and homogeneity of variance. Pearson's correlation test was performed to test the correlation between the mass density of the patellar tendon and its mechanical properties. The level of significance was set to 0.05 for both the *t*-test and correlation analysis. In order to determine if a value of mass density exists, above which the mechanical properties improve considerably, the following analysis was performed. First, the patellar tendons were ranked according to their mass density. We then randomly selected one of the calculated mass densities as a value that divides the patellar tendons into two groups with densities below and above it. Next, a *t*-test was performed to assess any differences that may exist in the mechanical properties between the two groups. The process was repeated until a mass density resulting in a significant difference between the properties of the two groups was found.

3. Results

The mean cross-sectional area of the specimens was 20.68 mm² (SD 8.72). The mean length of the patellar tendon was 50.93 mm (SD 3.78). The male patellar tendons, with a mean length of 52.34 mm (SD 3.42), were slightly longer than female patellar tendons having a mean length of 49.53 mm (SD 3.76) ($P = 0.05$, CI -0.57 , 6.2). The mean mass density of the patellar tendon tissue was 1.60 g/cm³ (SD 0.47) for the pooled population. The mass densities of the male (1.68 g/cm³) and female (1.52 g/cm³) patellar tendon were not significantly different ($P = 0.23$, CI -0.28 , 0.61). The range of the measured mass densities was found to be significant extending from a low of 0.76 g/cm³ to a high of 2.68 g/cm³ (250% difference).

The mechanical properties of the patellar tendon are independent of age and sex of the donor. The values of ultimate strength (σ_u), strain at failure (ϵ_f), elastic modulus (*E*) and strain energy density (*u*) of male and female patellar tendons are given in Table 3. Of the twenty patellar tendons tested, 19 failed in tendon substance, and one specimen failed by avulsion at the tibial attachment. We did not find any differences in the ultimate strength ($P = 0.62$, CI -18.1 , 13.2), ultimate strain ($P = 0.61$, CI -0.04 , 0.03), modulus of elasticity ($P = 0.57$, CI -142 , 118) or strain energy density

Table 3

Mechanical properties of the patellar tendon: classified by sex and the pooled population given as mean (SD)

	σ_u , MPa	ε_f	E , MPa	u , MPa
Male	57.5 (15.2)	0.18 (0.03)	501.4 (143.6)	4.37 (1.1)
Female	59.9 (17.2)	0.18 (0.04)	513.4 (134.1)	4.82 (0.8)
Pooled	58.7 (16.3)	0.18 (0.03)	507.4 (135.3)	4.59 (1.0)

($P = 0.84$, CI -1.35 , 0.45) based on sex. Also, no significant correlations ($r < 0.35$, $P > 0.05$) were found between the age and any of the mechanical properties of the patellar tendon in either of the sexes or when the populations were pooled. Since sex or age did not have any effects on the mechanical properties of the patellar tendon, all samples were pooled for correlation analysis with mass density.

The ultimate tensile strength ($r = 0.57$, $P < 0.02$, CI 0.17 , 0.8) and strain energy density ($r = 0.53$, $P < 0.02$, CI 0.11 , 0.78) of the patellar tendon were correlated to its mass density. Although the modulus of elasticity of the patellar tendon was also positively correlated to its mass density, the correlation was weaker than the other two but was statistically significant ($r = 0.44$, $P < 0.05$, CI 0 , 0.74). No correlation was found between the failure strain and the mass density of the patellar tendon ($r = -0.25$, $P > 0.1$, CI -0.62 , 0.22). A sample scatter plot showing the correlation of mass density with ultimate strength is presented in Fig. 3. A similar trend existed for both elastic modulus and strain energy density. No significant correlations were found between mass density and body anthropometry data ($r < 0.3$, $P > 0.1$).

The analysis based on successive t -tests revealed that the ultimate tensile strength of those patellar tendons

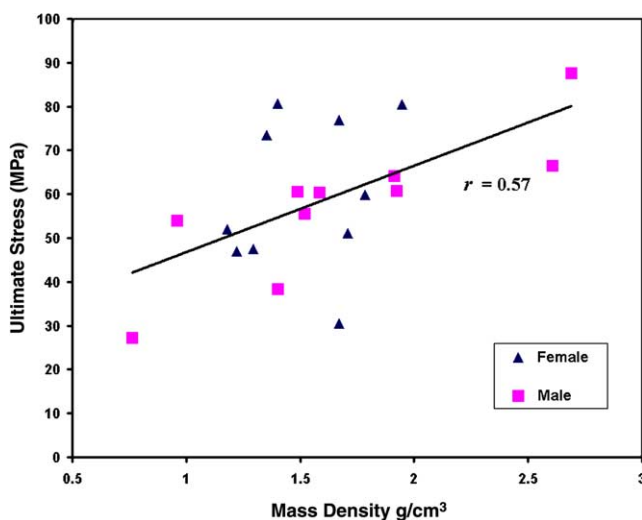


Fig. 3. Scatter plot showing the correlation between ultimate stress and mass density of patellar tendon. Noted increase in ultimate stress can be observed if the mass density is above 1.6 g/cm^3 . The correlation was similar for elastic modulus and toughness.

Table 4

Comparison of the material properties of patellar tendons having mass densities above and below 1.67 g/cm^3 given as mean (SD)

Density, ρ (g/cm^3)	n	Mean age, years	σ_u , MPa	E , MPa	u , MPa
$\rho < 1.67$	12	38.25	52.26 (15.83)	465 (132)	4.36 (0.84)
$\rho > 1.67$	8	38.41	68.38 (12.14)	570 (116)	4.94 (1.07)

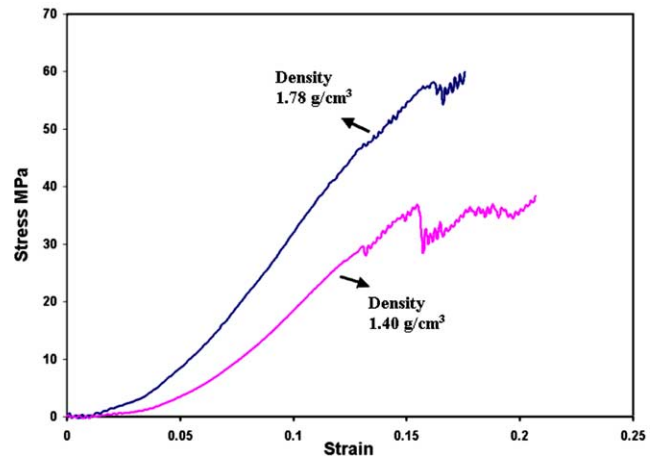


Fig. 4. Typical stress–strain curves for a low density (1.4 g/cm^3) and high density (1.78 g/cm^3) patellar tendon. The effect of mass density on strength, elastic modulus and strain energy density is clearly demonstrated.

having a mass density greater than 1.67 g/cm^3 ($n = 8$) was higher ($P < 0.02$, CI 2.21 , 30.03) than those with a density lower than 1.67 g/cm^3 ($n = 12$). Clearly, with more samples and tests this value may change slightly; therefore, we are not reporting this value as a critical value but simply as evidence that such a value, or a corresponding range, may exist. A similar trend was observed for modulus of elasticity ($P < 0.05$, CI -17 , 228). However, no such value was found in the case of toughness ($P = 0.09$, CI -0.32 , 1.48). Mechanical properties of patellar tendons having mass densities above and below 1.67 g/cm^3 are given in Table 4. Representative stress–strain curves of two specimens of mass densities below and above 1.67 g/cm^3 are shown in Fig. 4.

4. Discussion

We found no evidence of a significant difference in mechanical properties of the patellar tendon based on sex in humans. Although there is evidence that female sex hormones can affect the mechanical properties of connective tissues in animal models (Slauterbeck et al., 1999; Rasanen and Messner, 2000), it seems that such effects are not significant in the case of human patellar tendons. However, Kubo et al. (2002) found a significant difference in the mechanical properties of human

medial gastrocnemius tendon muscle between males and females. We believe that the different results observed between different animal models, different tissues and between the sexes are related to the variable response to sex hormones and remodeling of collagen and other matrix molecules. Therefore, one may conclude that any sex-based differences in the mechanical properties of connective tissues are tissue and animal specific. Since there is no sex-based difference in failure strength of the patellar tendon, this may be one reason why [Shelbourne et al. \(1998\)](#) did not find sex-based differences in the reconstructed (using autograft) anterior cruciate ligament tear rate. However, the question remains whether such differences exist in the properties of the human ACL based on sex. Further research is needed to answer this question.

The calculated mass densities of the patellar tendons in our research revealed a large range: from a low of 0.76 g/cm^3 to a high of 2.68 g/cm^3 (a 250% difference). Although factors such as genetics, diet and activity level may be the cause for the existing variability in the mass density, further research is needed to illuminate the main causes.

In this study, the mass density of the tissue was considered as a variable for correlation analysis. By considering mass density, the effect of tissue size on the correlation analysis is removed. We calculated mass density using wet weight instead of dry weight for two reasons: (1) The results will be directly applicable in the clinical applications such as ACL reconstructions using autografts and (2) measuring the accurate tissue dimension in dry condition is difficult and hence calculation of mass density will be inaccurate.

We found a significant correlation between the mechanical properties and mass density of the patellar tendon. This is an interesting and important finding considering the fact that no graft quality tests are available to a surgeon before an ACL reconstruction. A higher tissue density may reflect higher amounts of collagen that are closely packed in the tissue resulting in superior mechanical properties. [Woo et al. \(1981\)](#) determined that the mass and collagen content of swine digital extensor tendons increased as a result of exercise and resulted in a significant increase of its ultimate tensile strength but decreased the ultimate strain. A correlation study between mechanical properties and mass of the tendons was not performed in that study. Though we found a negative correlation ($r = -0.25$) between the ultimate strain and mass density, the correlation was not statistically significant. Our results, in general, are similar to those of [Woo et al. \(1981\)](#). Our results are also similar to that of [Haut et al. \(1992\)](#) who found the elastic modulus of canine patellar tendon increased with its collagen content. However, they did not measure tissue mass or mass density in that study. Unfortunately, we are not able to correlate the variation in mass densities

in our study to exercise or any other activity of the donors as the donor activity level is unknown to us. The mechanical properties of patellar tendons are reported to be region specific ([Haraldsson et al., 2005](#)) with anterior fascicles having superior mechanical properties. The difference in mass densities and the relationship between mass density and mechanical properties of these individual fascicles may lead to further insight into this issue.

Furthermore, we found a value for mass density of the tissue (1.67 g/cm^3) above which the mechanical properties are significantly superior as shown in [Table 4](#). Since the mean age of donors above and below this value of density is very similar, one may conclude that any differences in properties are not due to age. This is also an independent verification of a lack of correlation between age and the strength of the patellar tendon in the age range studied in this paper. Unfortunately, none of the earlier studies on patellar tendon biomechanics measured tissue density.

As presented in [Table 1](#), there exists a wide range of reported values for the mechanical properties of the patellar tendon. Factors such as sample size, tissue preservation procedures, tissue environment during testing ([Haut and Powlison, 1990](#)), cross-sectional area of the tested tissue, and mechanical testing procedures are all important and significantly different in the reported studies. Accordingly, it is difficult to make a case-by-case comparison. There is evidence in the literature that the use of the saline bath results in a stronger and stiffer patellar tendon due to restricted fluid flow out of the tissue during the test ([Haut and Powlison, 1990](#)). Differences in strain rate used in the reported studies might not have a significant effect on the mechanical properties ([Blevins et al., 1994](#)). This can be verified by comparing the results of the above two studies. While [Johnson et al. \(1994\)](#) reported that all of their specimens failed at the tibial attachment site, a majority of our specimens (75%) failed at tendon sites away from attachment and 20% of the specimens failed at the attachment site. This can be attributed to the higher strain rate used in our study. Higher strain rate may influence the failure mode without significantly influencing the tensile properties. The failure modes in our study are consistent with [Butler et al. \(1986\)](#) who reported that, in younger donors, patellar tendons most often fail intrasubstance. Some researchers, observing the variation in biomechanical behavior of the patellar tendon, suspected that there might be some other intrinsic or extrinsic factors contributing to the variability. For instance, [Flahiff et al. \(1994\)](#) stated that factors such as weight, activity level, health or diet may influence the properties of patellar tendons, while [Beynon et al. \(2001\)](#) stated that unknown biologic factors intrinsic to soft tissue may result in variation in their behavior. Based on our research, the mass density of patellar tendons seems to be a reason for some of this variability.

We did not find any evidence of a significant correlation between donor age and any of the mechanical properties of the patellar tendon. This is consistent with the results reported by Flahiff et al. (1994) and is partly consistent with results obtained by Blevins et al. (1994) who reported a weak negative correlation between the modulus of elasticity and age. In their study, although the sample size is high (82), the patellar tendon samples were harvested from 25 donors. Thus, the study achieves high statistical power without adding significant variability. Johnson et al. (1994) compared the mechanical properties of the patellar tendon in two age groups of 29–50 and 64–93. Their study showed a lower tensile strength in the older group but other properties were found to be similar. A correlation analysis between age and mechanical properties was not performed within any of the groups or in the pooled population, thus a meaningful comparison between the current study and that by Johnson et al. (1994) is not possible. Our study does not preclude the possibility that there may be a reduction of PT strength above 50 years of age.

The most significant conclusion of this study is that the mass density of the patellar tendon may be used to assess the mechanical quality of the tissue. This finding could have clinical importance. There are some researchers who believe it is important to predict the biomechanical behavior of autografts prior to reconstruction procedure Beynnon et al. (2001) reported that those allografts that had elongation not similar to that of intact ACL resulted in excessive anterior posterior laxity of the knee after 5 years. These researchers also state that since measurement of graft elongation immediately after reconstruction is important but difficult to perform, certain simple indicators are necessary to predict biomechanical properties of the autogenous grafts. Based on our research, the mass density of the autograft may be used to predict the biomechanical properties of the graft including elastic modulus. Fortunately, modern imaging techniques such as CT scans (Mull, 1984) can be used to measure the mass density of graft tissues non-destructively. A calibration curve, which correlates the mass density of the tissue with its CT number, is needed to find the mass density of the tissue from CT scans. Therefore, in vivo measurement of the mass density of the patellar tendon, prior to surgery, can be used to decide if a particular ACL reconstruction should be carried out with an allograft or an autograft.

Although we did not find sex-based differences in the mechanical properties of patellar tendons, adequate power was not achieved (<50%). This was because of small differences in the mechanical properties between the sexes. In addition to the fact that a large sample size (>200) is required in order to detect such a small difference, we believe such a sex-based difference, even if it exists, would be too small to cause any significant variability in patellar tendon biomechanics. Though

we made every attempt to maintain tissue hydration during the tests, some amount of dehydration may have occurred. Testing the tissue in a saline bath is a better method than the open-air test we used since the in vivo environment of the graft is similar to the environment in bath. Further research that correlates the mass density to collagen content of the tissue and its ultrastructure is needed to verify our findings. Further research should also be directed toward finding similar correlations between the mass density and mechanical properties of allografts. The results obtained here may not be applicable to allografts since they are irradiated and freeze-dried before use in reconstruction surgery.

5. Conclusion

There is no evidence of a sex-based difference in the mechanical properties of the patellar tendon. The mass density of the patellar tendon may vary significantly from one donor to another (by as much as 250%), and this could heavily influence its mechanical properties. Our study suggests that grafts with densities lower than 1.67 g/cm³ are mechanically inferior to grafts with higher mass density. More research is required to determine the implications of using low-density grafts for ACL reconstruction. Biochemical and histological studies are needed to verify the effect of mass density on patellar tendon mechanical properties.

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