Biomechanical Analysis of Patellar Tendon Allografts as a Function of Donor Age*

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ABSTRACT

We evaluated the biomechanical properties of patellar tendon allografts from donors aged 18 to 55 years. Bone-patellar tendon-bone complexes were harvested from acceptable donors and processed. Fat and soft tissue were removed, and the tendons were sectioned lengthwise leaving the central third. Area measurements were taken, and mechanical testing was performed. Specimens were pulled to failure at a rate of 10% of the initial length per second. The force at failure, tensile stress, modulus of elasticity, and percent elongation were determined for each specimen. There was no significant correlation (P > 0.05) between age and any of the mechanical properties. Load at failure ranged from 2110 to 4650 N, with a mean of 3424 N. Regression analysis showed slightly decreasing tensile stress with increasing age, but the correlation was not significant. It appears that patellar tendon allografts from donors up to age 55 have similar mechanical properties.

Anterior cruciate ligament reconstruction is becoming an increasingly popular procedure as the natural history of the ACL-deficient knee is more clearly defined. Feto and Marshall concluded that the fate of the ACL-deficient knee was “progressive deterioration and dysfunction.” In some patients, the instability created by the absence of an intact ACL has been shown to lead to meniscal tears, stretching of the secondary restraints, and possibly traumatic arthritis. In delicato and Bittar, in their retrospective review of ACL-deficient knees, found that meniscal injuries increased from 77% in knees with acute insufficiency to 91% in those with chronic ACL insufficiency. Anterior cruciate ligament replacements used in the reconstruction of the ACL-deficient knee must meet certain requirements. These replacements, which are most commonly autograft or allograft tissue, must be of sufficient tensile strength, possess low immunogenicity, provide immediate stability allowing early motion, show little degeneration over time, and must be inserted with minimal surgical complications.

Autogenous tissue used for ACL reconstruction includes the patellar, semitendinosus, gracilis, and quadriceps tendons, and the iliotibial band. The patellar tendon autograft is one of the most popular substitutes for the ACL. It is one of the strongest autografts available for ACL reconstruction, and it is thought that removal of the central third of the width of the patellar tendon does not significantly decrease knee stability. Concerns with harvesting bone-patellar tendon-bone autografts, however, include alterations in patellofemoral tracking, patellar tendinitis, patellofemoral pain, rupture of the patellar tendon, and patellar fracture. To address these potential problems, allografts have been introduced as an alternative to autogenous tissue for ACL reconstructions.

Allografts have several advantages over autografts. They result in no donor site morbidity, decrease total operating time, and improve cosmesis. Allografts are also the only biologic alternative when autograft tissue fails. However, allograft tissue can be limited in supply and has the potential to transmit disease or undergo rejection. Soft tissue allografts that have been used for ACL reconstruction include fascia lata, Achilles tendon, bone-ACL-bone complexes, and bone-patellar tendon-bone complexes. The patellar tendon allograft is the most frequently used allograft for ACL replacement and the strongest biologic substitute. Noyes et al. examined several human tissues used for ACL reconstructions and found that the central third (14 mm) of the patellar tendon had the highest strength: 168% of the ACL tensile strength. Because it is transplanted with the patellar and tibial attachments, the patellar tendon graft allows bony fixation in the femoral and tibial tunnels. It also quickly revascularizes and can be cut to the appropriate size and shape at the time of

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surgery. Freezing reduces the immunogenicity of the graft and increases the rate of incorporation. Freeze-drying further reduces the immunogenicity to a level below that which can be detected by most assay techniques. Although freezing and freeze-drying result in nonviable cells, the graft acts as a scaffold for infiltrating cell growth. Strength of the graft is not thought to be significantly compromised with deep freezing or freeze-drying.12,14,22

Because of the success with and subsequent increase in use of patellar tendon allografts, they have decreased in availability. Although few biomechanical studies have been conducted regarding donor age, it is generally thought that grafts from younger donors have better mechanical properties. Jackson and Kurzweil12,15 recommend using grafts from donors less than 35 to 40 years of age for ACL reconstructions. For the ACL, the maximum stress, ultimate load, and elastic modulus have been shown to decrease with age.21,23 For patellar tendons, Blevins et al.1 found no difference in the tensile strength and elastic modulus from donors 17 to 54 years old. Johnson et al.17 found that patellar tendon tensile strength decreased between younger (29 to 50 years) and older (64 to 93 years) age groups. However, the elastic modulus, strain, and viscoelastic behavior were not affected by age. Since patellar tendon allografts from donors older than 35 to 40 years may be of sufficient strength for ACL reconstructions and since availability of grafts from young donors is limited, this study was conducted to determine the relationship between donor age and the biomechanical properties of patellar tendon allografts.

MATERIALS AND METHODS

Specimens of the patellar complex, consisting of the intact proximal tibia, patellar tendon, and patella were obtained fresh frozen from the Musculoskeletal Transplant Foundation (Holmdel, NJ). All specimens were obtained from donors, 18 to 55 years old (mean ± SD, 39.6 ± 12.0), who met the requirements of the tissue bank for bone and tissue donation. Medical histories were obtained, and the donors had no chronic disease and no coexisting systemic disease. The specimens were sterilized harvested according to the protocol of the American Association of Tissue Banks for tissue procurement. These tissues were processed and fresh frozen for the purpose of tissue transplantation. The specimens obtained for this study were subsequently rejected for transplantation because of bacterial contamination, but they were structurally intact. A total of 39 specimens were obtained for mechanical testing. The specimens were kept frozen at −40°C until testing, and all specimens were tested within 1 month after they were received.

Before mechanical testing, the specimens were thawed, and fat and soft tissue were removed. The tendon was sectioned lengthwise leaving the central 13 mm, approximately one third of the width. The tibial tubercle and patella remained intact to facilitate mechanical testing. A 1.0-N preload was applied to remove tendon laxity, and length and area measurements were taken with a digital micrometer (NSK Max-Cal, Jensen Tools, Phoenix, AZ). For the length measurement, the posterior of the tendon was measured between the two bones. Two measurements were taken and averaged. The cross section was assumed to be rectangular. Width and thickness were measured at four sites along the length of the tendon and averaged. Measurements were taken such that the soft tissue did not deform with micrometer contact. Specimens were periodically moistened with saline to minimize dehydration.

For mechanical testing, the bones were left intact since gripping the tendon results in tearing at the clamp rather than midsubstance. The tibia and patella were mounted in fixtures using low-melting point metal (Bismuth Alloy, #JLMA-158, Small Parts, Miami, FL). Screws were first placed in the tibia to hold the bone in the metal. As metal was poured around the patella, cold water was simultaneously poured over the tendon to protect it from thermal injury. Ice was then used to harden the metal. The specimens were pulled to failure using a materials test system (MTS Bionix, Minneapolis, MN) at a strain rate of 10% of the initial length per second, which provided an identical strain rate for all the specimens. A custom-made table was mounted to the load cell to align the tendon with the loading axis. Force and displacement were recorded using a Macintosh II computer (Apple Computer, Inc., Cupertino, CA) with a 16-bit (26 bits) resolution analog-to-digital converter and LabView software (National Instruments, Austin, TX). Failure mode was also noted. For specimens that failed at the bone, only the force at failure was noted. For each specimen that failed at midsubstance, the ultimate tensile stress, percent elongation, and modulus of elasticity were determined. Percent elongation was indirectly measured by the grip-to-grip displacement. Modulus of elasticity was calculated from the linear part of the load versus displacement curve and the area and length measurements. For statistical analysis, regression analysis was calculated using StatView (Abacus Concepts, Berkeley, CA). Significance was considered to be P < 0.05.

RESULTS

The load at failure, ultimate tensile strength, percent elongation and modulus of elasticity values for specimens that failed at midsubstance (N = 33) are presented in Table 1. The load at failure ranged from 2110 to 4654 N, with a mean of 3424 ± 668 N (±SD). Specimen age did not affect the failure load (P = 0.4) (Fig. 1). The ultimate tensile

| Table 1 |
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| Mean values of the mechanical properties for patellar tendon allografts with midsubstance and bony failures |
| Failure mode | Mean ± SD | P value* | r value* |
| Midsubstance failures (N = 33) | | | |
| Load at failure (N) | 3424 ± 668 | 0.41 | 0.15 |
| Ultimate stress (MPa) | 78.4 ± 18.5 | 0.22 | -0.22 |
| Modulus (MPa) | 340 ± 97 | 0.40 | -0.17 |
| Percent elongation at failure | 31.4 ± 5.9 | 0.85 | -0.04 |
| Width (mm) | 13.2 ± 0.67 | 0.14 | 0.07 |
| Bony failures (N = 6) | Load at failure (N) | 1830 ± 614 | 0.98 | 0.02 |

* Correlation with age.
stress for these specimens is shown in Figure 2. A regression curve shows that the ultimate tensile strength decreased slightly with age, but this correlation was not significant \((P = 0.2)\). No significant correlation with age was seen regarding the percent elongation at failure \((P = 0.8)\); which ranged from 22.1 to 47.8 with an average of 31.4 ± 5.9 mm (Fig. 3). Similarly, there was no significant correlation \((P = 0.4)\) between the modulus of elasticity and specimen age (Fig. 4). The average or mean cross-sectional area for the specimens was 45.0 ± 1.5 mm², and the width was 13.2 ± 0.7 mm.

The tip of the patella broke in six specimens (15%). These bony failures occurred in specimens from donors aged 24 to 55 years, with an average age of 43. Load at failure values for these specimens, which ranged from 860 to 2418 N with an average of 1830 N, were significantly lower \((P = 0.0001)\) than for specimens with midsubstance failures. There was no correlation, however, between age and failure mode \((P = 0.5)\).

![Figure 1](image1.png)  
**Figure 1.** Regression curve for load at failure versus specimen age.

![Figure 2](image2.png)  
**Figure 2.** Regression curve for ultimate tensile strength versus specimen age.

![Figure 3](image3.png)  
**Figure 3.** Regression curve for percent elongation at failure versus specimen age.

![Figure 4](image4.png)  
**Figure 4.** Regression curve for modulus of elasticity versus specimen age.

**DISCUSSION**

Allograft tissue is typically obtained from donors less than 45 to 55 years old. Jackson and Kurzweil recommend using patellar tendon allografts from donors younger than 35 to 40 years of age, although little biomechanical data have been reported for tendon allografts with respect to donor age. Johnson et al. determined that there was a decrease in tensile strength when comparing patellar tendons from donors over age 64 to those under age 50. We found no correlation between age and the force at failure, ultimate tensile stress, percent elongation, and modulus of elasticity when evaluating patellar tendons from donors between 18 and 55 years old.

Failure of the patellar tip occurred in 15% of the specimens tested. The load at failure was significantly less for patellar tip failures than for midsubstance failures. Failures at the patellar tip may contribute to the in vivo failures that occur at the bony attachments rather than in midsubstance. However, there was no correlation between patellar tip failure and age.
There was considerable variability in the data as seen by the large standard deviations. This indicates that most of the variability in the strength of a specimen is due to individual differences rather than age. Other factors, such as weight, activity level, health, or diet may have more influence on patellar tendon strength than does age. Thus, another variable other than age may be a better indicator of allograft strength. Hubbard and Soutas-Little tested tendons from the hands and feet of cadavers aged 16 to 88 years and found no correlation in tensile stress or elastic modulus with age. Large variability was found, even within the same subject, and it was concluded that "an age effect may have been masked by other variables, possibly health, diet, disease, or exercise."

Unlike some of the previous patellar tendon studies, we used a strain rate of 10% instead of 100%. This rate was selected to maximize the amount of data collected. Although failure usually occurs clinically within 1 second, a strain rate of 10%, consistent for all specimens, was thought to be acceptable for determining the effect of donor age on the tendon's biomechanical properties. Additionally, Blevins et al. found no difference in the tensile strength with 10% versus 100% strain rate.

The force at failure values obtained in this study were higher than those obtained by Noyes et al. when they tested young trauma victims (3424 versus 2900 N). The higher values obtained in this study may be due to differences in specimen preparation or testing procedure. In their study, the patellar tendon was dissected from the bony attachments, while in this study the tendon remained attached to the tibial tubercle and patella. Rather than using clamps to grip the tendon, the tendon was pulled by way of the bony attachments, which may have resulted in the higher load at failure. The bones were left intact since gripping the tendon resulted in failure at the clamp site rather than subchondrally. Cooper et al. tested patellar tendons with the bony attachments intact and found higher failure loads than those reported by Noyes et al. for specimens approximately 14 mm in width. The failure loads seen in this study, 3424 N for specimens 13 mm in width, agree with those of Cooper et al., who found loads of 3657 and 4389 N for specimens 10 and 15 mm in width, respectively. The ultimate tensile stress in this study (78.4 MPa) was found to be between those reported by Noyes et al. and Cooper et al. (58.3 and 97.5 MPa, respectively). These data, as well as that reported by Cooper et al., suggest that the central third of the patellar tendon may be stronger than previously acknowledged.

A recent study by Woo et al. has shown that ACL strength may be higher than previously reported. Mechanical testing of the ACL in its anatomic orientation resulted in a failure load of 2160 N for a young age group, compared with that of 1725 N reported by Noyes et al. A slower elongation rate (approximately 10% per second) was used by Woo et al. Compared with the data reported by Woo et al., the data in this study suggest that the central third of the patellar tendon has approximately 150% of the strength of the ACL.

Unlike the ACL, the patellar tendon did not show a decrease in tensile strength with age. This difference may be owing to the structure of the patellar tendon or differences in composition, environment, and function between tendons and ligaments. Since no difference in mechanical properties was found in specimens up to age 55, patellar tendon allografts from donors up to age 55 may be suitable for ACL replacement. Moreover, if the strength of patellar tendons decreases less with age compared with the ACL, the strength of the patellar tendon, as a percentage of ACL strength, could be expected to increase with respect to age.

This study shows that before surgery there is no correlation between age and biomechanical properties of patellar tendon allografts from donors up to age 55. Although the strength of the tendon decreases after implantation, it is expected that the strength would then increase with time because of healing and revascularization. The strength, however, would probably not increase to the original strength. There was considerable variation in the mechanical properties from donor to donor, and age was not a reliable predictor of tendon strength. The values obtained indicate that patellar tendons may be stronger than shown in some of the earlier studies. Based on these data, we believe patellar tendon allografts from donors up to age 55 should be of sufficient strength for ACL replacement.

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REFERENCES


