A Biomechanical Comparison of Three Lower Extremity Tendons for Ligamentous Reconstruction About the Knee

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Purpose: The purpose of this investigation was to evaluate 3 previously unreported allograft tendons for use in knee surgery. These are the doubled tibialis anterior (TA), doubled tibialis posterior (TP), and doubled peroneus longus (PL) tendons. **Type of Study:** A biomechanical evaluation of the properties of the TA, TP, and PL. **Methods:** Sixteen fresh-frozen cadaveric lower limbs were used for testing. All specimens had the TA, TP, and PL tendons harvested. All specimens were tested in a custom-designed hydraulic testing machine using dry ice clamps. Each tendon was elongated at a rate of 1 mm/s. Load and displacement were recorded with an analog to digital interface board. Stiffness, modulus of elasticity, and stress and strain at failure were calculated. **Results:** The average tested lengths of the TA, TP, and PL were 37 cm (range, 13-68 cm), 33 cm (range, 7-74 cm), and 42 cm (range, 17-69 cm), respectively. The average cross-sectional areas of the doubled TA, TP, and PL were 38 mm^2, 48 mm^2, and 37 mm^2, respectively. The average failure loads for the doubled TA, TP, and PL tendons were 3,412 N, 3,391 N, and 2,483 N, respectively. The maximum stresses of the 3 tendons did not differ significantly (85-108 Mpa). The TA had the greatest stiffness (344 N/mm), followed by the TP (302 N/mm) and the PL (244 N/mm). Previous authors have documented the biomechanical strength of grafts for ACL reconstruction between 1,700 and 2,900 Newtons. The ultimate tensile strength and stiffness reported for the TA and TP grafts exceeded that for all previously reported grafts, including the doubled semitendinosus-gracilis. **Conclusions:** The TA, TP, and PL tendons showed excellent biomechanical properties when compared with historical data evaluating other graft sources. The biomechanical properties observed for the TA, TP, and PL were noted in specimens despite an average age of 78.3 years. **Key Words:** Allograft—Ligament—Reconstruction—Knee—Anterior cruciate ligament.

The functional significance of the cruciate ligaments is well established, with anterior cruciate ligament (ACL) reconstructions performed frequently throughout the United States. In addition, multiple ligamentous injuries resulting from vehicular or sports trauma often require surgical reconstruction as well. Among the critical factors in the successful outcome of such a reconstruction is the choice of graft material.[1-9] In many instances, autologous tissue is harvested to reconstruct the cruciate or collateral ligaments. Commonly used graft sources are the central third of the patellar ligament or doubled semitendinous and gracilis tendons. In addition, other graft sources have been described, including the central third of the quadriceps tendon and fascia lata.[2,10-17]

In an effort to further decrease surgical morbidity, facilitate revision surgery and improve postoperative rehabilitation, some surgeons have advocated the use of various allograft tissues for surgical reconstruction of the ACL. Proponents of allograft use point out the decreased operative time, lack of donor site morbidity,

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the capability of bone to bone fixation, and diminished postoperative pain.[18-22] In addition, in the case of multiple ligamentous injuries, unlimited allograft tissue can be made available whereas autologous tissue is limited. To date, the most frequently used allograft materials for ACL reconstruction include patellar ligament, quadriceps tendon, and Achilles tendon.

The purpose of the current investigation was to biomechanically evaluate 3 previously unreported allograft tendons for use in knee ligamentous reconstruction: doubled tibialis anterior (TA), doubled tibialis posterior (TP), and doubled peroneus longus (PL) tendons. It was our goal to evaluate the biomechanical properties of these tendons in a double-looped fashion. The biomechanical properties of these grafts were compared with values reported for the native anterior cruciate ligament and other reported graft sources for ACL reconstruction.

METHODS

Sixteen fresh-frozen cadaveric lower limbs were obtained from the University Anatomical Gifts Program. The average age of the tested specimens was 78.3 years (range, 66-89 years). Specimens were frozen at −20°C and thawed at room temperature the day of harvest. All specimens had the TA, TP, and PL tendons harvested from the musculotendinous junction to its insertion. All specimens were inspected for tendonitis, and any tendon that showed evidence of such was discarded. Each tendon was labeled in a separate container and frozen at −20°C until the day of testing. On the day of testing, each tendon was thawed at room temperature, and the cross-sectional area was measured at 3 locations along the tendon. The total length of each specimen tendon was not measured each time. Three measurements were taken of each tendon, and the average was recorded as the final measurement. Cross-sectional area was measured with the tendons placed in both single- and double-stranded configurations.

All specimens were tested in a custom-designed and constructed hydraulic testing machine. Before testing, each end of the tendon was placed in a freezing clamp that was connected to the hydraulic testing machine (Fig 1). Dry ice was inserted into the ice receptacles of the tendon clamps, and tension was removed from the tendon. After the application of dry ice, approximately 3 minutes was allowed for the tendon ends to freeze within the clamps. Time was measured as a dependent variable with tissue freezing as the controlling factor. The tendon was allowed to freeze until freezing was observed just outside (1-2 mm) the clamp, but not long enough for the freezing to advance beyond. The actual time varied about the average based on the initial temperature of the clamp. All tendons were examined before testing. They were cold but not frozen, except approximately 1 to 2 mm adjacent to the clamp. The distance between the clamps was measured, and each tendon was elongated to failure at a rate of 1 mm/s. This rate is similar to strain rates reported in other studies.[23-25] Load and displacement were recorded on a computer with an analog to digital interface board (National Instruments, Austin, TX). Stiffness, modulus of elasticity, and stress and strain at failure were calculated using the linear portion of the load elongation curve and the recorded failure force. The loading rate, displacement measurement, and load cell calibration were all verified using known standards before initiation of the study.

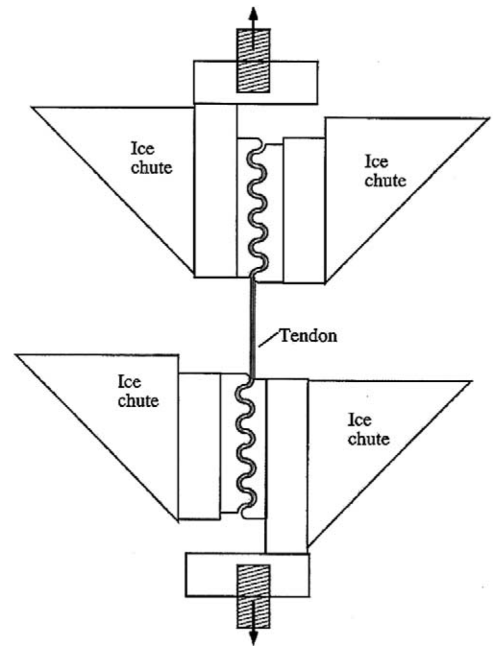

FIGURE 1. Tendon freezing clamp.

Statistical analysis was performed using a 1-way analysis of variance with the 3 tendon groups (Abacus Concepts, Berkley, CA). A paired *t* test was used to compare values between groups.

RESULTS

For purposes of the study, tendons tested were placed into 1 of 3 groups: group 1: TA; group 2: TP; and group 3: PL. The average lengths of the TA, TP,

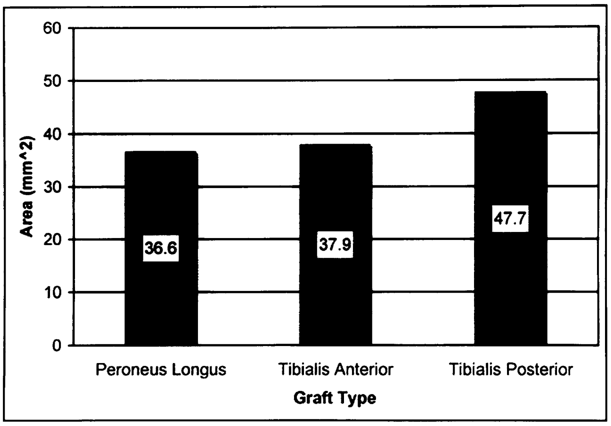

FIGURE 2. Average cross-sectional area of doubled tendons.

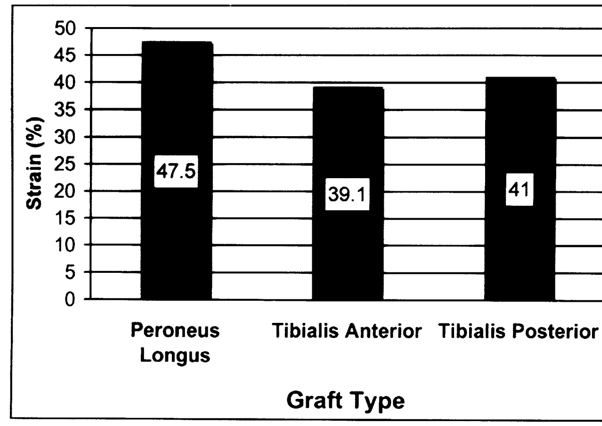

FIGURE 4. Ultimate strain of doubled tendon.

and PL tendons were 37 cm (SE, ± 4.0), 33 cm (SE, ± 4.3), and 42 cm (SE, ± 3.4), respectively. The average cross-sectional areas of the doubled TA, doubled TP, and doubled PL tendons were 38 mm^2, 48 mm^2, and 37 mm^2, respectively. No statistical difference was seen among the groups ($P < .23$) (Fig 2). No significant difference was seen in the lengths of tendons tested. The average ultimate loads to failure for the doubled TA, TP, and PL tendons were 3,412 N, 3,391 N, and 2,483 N, respectively. No statistical difference was seen in the ultimate failure loads of the doubled TA and TP tendons ($P = .96$). A statistical difference in ultimate failure load was noted when the tibialis anterior and tibialis posterior were compared with the peroneus longus ($P < .04$ and $P < .05$, respectively) (Fig 3). The maximum stress of the 3 tendons did not differ significantly (85-108 Mpa). The modulus of elasticity was not significantly different between the doubled tibialis posterior (208 kPa) and the doubled peroneus longus tendons (243 kPa). However, when compared with the doubled tibialis anterior (453 kpa), both the tibialis posterior and peroneus longus differed significantly ($P < .03$ and $P < .01$ respectively).

Ultimate strain varied among all groups, with the doubled TA having the lowest value (39%) and the doubled TP having the largest (68%) (Fig 4). Stiffness varied significantly among the 3 groups, with the doubled TA having the greatest stiffness (344 N/mm), followed by the doubled TP (302 N/mm), and doubled PL (244 N/mm) (Fig 5).

Eight tendons (4 TA, 2 TP, and 2 PL) slipped during testing, and these data were not used for calculations. All tendon slippage occurred in the initial stages of the study and was likely caused by incomplete freezing of the tendons within the clamp. After the appropriate

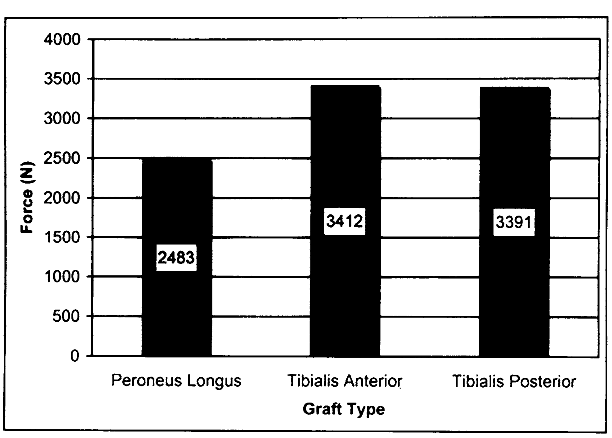

FIGURE 3. Average maximal failure load of doubled tendons.

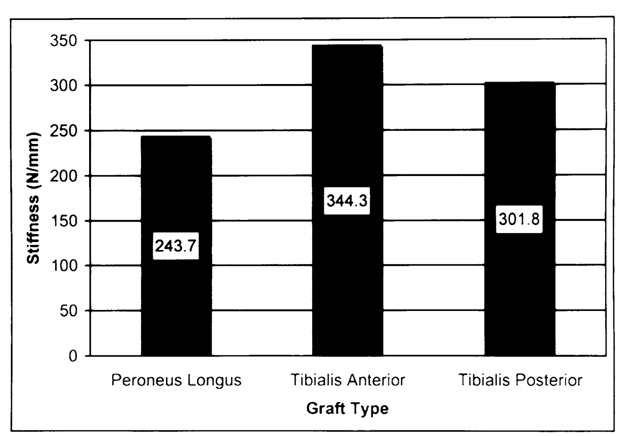

FIGURE 5. Average doubled-strand stiffness.

freezing time and tendon freezing was noted, no slippage occurred for the remainder of experimental testing.

DISCUSSION

Over the past 15 years, the patellar ligament has been frequently used as a graft source for reconstruction of the ACL. The popularity of this graft stems primarily from its high initial strength, potential for bone-to-bone healing, and the predictable success in achieving knee stability.[4,5,9-11,26] However, the morbidity associated with the use of the patellar ligament has been well described. Problems encountered have included donor site morbidity, patellofemoral pain, quadriceps weakness, patellar ligament rupture, patellar fracture, and loss of motion.[2,10,27-30] In an effort to diminish the morbidity that has been associated with the use of the patellar ligament, other graft sources have been reported. These include the use of double-looped semitendinosus and gracilis tendons, in addition to the central third quadriceps tendon.[2,7,10-12,31] Proponents of hamstrings use report less morbidity and quadriceps muscle weakness associated with graft harvest than with use of the patellar ligament.[2,6,8-11,31-35]

Recently, the central third quadriceps tendon has been reported as a graft source for ACL reconstruction. Proponents of this graft note a 50% increased collagen content over a similarly sized patellar ligament graft.[12] However, quadriceps muscle weakness and patellofemoral pain have still been reported with the use of a quadriceps tendon graft.[12]

The use of allografts for isolated or multiple ligamentous reconstruction has been reported, with excellent long-term knee stability and subjective clinical ratings noted.[36-38] However, their use is not without drawbacks. Opponents of allografts underscore cost, the risk of disease transmission, and past reports of osteolytic reactions at the allograft–host bone interface.[39-42] Many of the early reports of allograft osteolysis were in patients who had grafts sterilized with high doses of radiation (>2.5 Mrads) or with ethylene oxide.[43-45] Neither of these sterilization techniques is currently used for most allografts in use today. Recently, deep freezing (−80°C) or cryopreservation in conjunction with bacteriologic and steriologic testing has virtually eliminated the risk of disease transmission with allograft use.[46-49]

With the reported excellent results after allograft reconstruction, demand for these grafts has increased. Unfortunately, an adequate number of appropriate donors are often not available to meet the demand for these grafts. As a consequence of the limited supply of allograft tissue, we wanted to biomechanically evaluate several potential graft sources for ligamentous knee reconstruction.

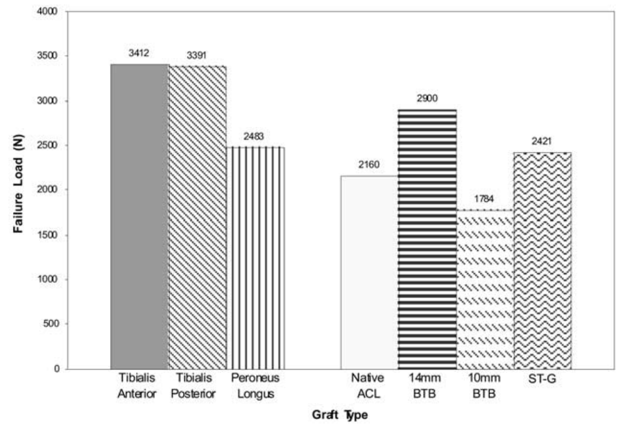

FIGURE 6. Ultimate failure loads of different grafts compared with doubled tibialis anterior, tibialis posterior, and peroneus longus.

Previous authors have documented the biomechanical strength of the ACL and various graft sources. Noyes et al.[9] and Woo et al.[50] both found the ultimate tensile strength of the native ACL in the young adult to approach 2,160 N. This value was greater than that reported for a 10-mm autologous graft (1,784 N), but less than the value cited for a 14-mm autologous patellar tendon graft (2,900 N) or a doubled semitendinosus-gracilis (STG) graft (2,421 N).[9,50,51] The UTS that we showed for the doubled TA, doubled TP, and doubled PL tendons compares favorably with this historical data. Moreover, the ultimate tensile strength for the TA and TP grafts far exceeded the ultimate tensile strength of all previously reported grafts, including the doubled STG (Fig 6).

Data on stiffness for various grafts has also been reported, with a range of 210 N/mm for a 10-mm autologous patellar tendon graft to 274 N/mm for a 14-mm autologous bone–patellar tendon–bone graft.[9,51] The stiffness values recorded for all 3 grafts (242-344 N/mm) exceeded historical reports for all graft types (Fig 7). We should note that although we are unaware of previously published data evaluating the biomechanical properties of these tendons, other authors have cited the clinical use of the TA for ACL reconstruction.[52]

In the current study, we used a strain rate of 1 mm/s, which corresponds to an elongation rate of approximately 5%/s. This rate is similar to that used by other authors performing ligamentous testing. Woo et al.[23]

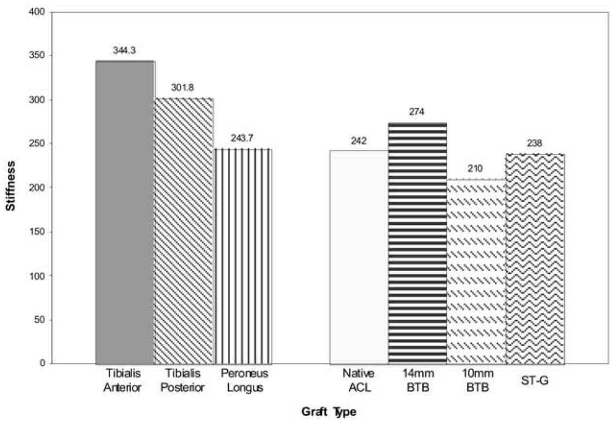

FIGURE 7. Stiffness of different grafts compared with doubled tibialis anterior, tibialis posterior, and peroneus longus.

used a strain rate of 0.33 mm/s in an ACL-testing study. Trent et al.[24] and others[25] have also used strain rates ranging from .83 to 8.3 mm/s in ligament testing studies. Other authors have used testing strain rates of 100%/s, because this rate is thought to produce soft tissue disruption before bony avulsion in the clinical setting.[9,51] One limitation of the current study is that tendon testing was not performed at different strain rates, which may have lead to different values for ultimate failure load and stiffness. However, the effect of strain rate on failure mode is not a factor in this study because no bone–tendon–bone specimens were tested.

The current study evaluated only the intitial biomechanical properties of these grafts. The pullout strength after initial fixation, as well as the clinical incorporation and function of these grafts, was beyond the scope of this study.

We should note that the specimens from whom the tendons were tested in the current study averaged 78.3 years of age. That excellent biomechanical results were seen in specimens of this age is noteworthy. This observation is important because specimens under the age of 40 years are usually required to provide adequate biomechanical strength for ligamentous reconstruction. Our data indicate that older specimens could be potential candidates for allograft donation, thereby increasing the donor pool for these grafts.

In conclusion, the current study biomechanically evaluated 3 allograft tissues for potential ligamentous reconstruction within the knee. The doubled TA, doubled TP, and doubled PL tendons showed ultimate tensile strength and stiffness that were equal to or exceeded nearly all currently described ACL graft sources. In addition, these grafts were obtained in older individuals, indicating that grafts procured from younger donors may show even improved biomechanical properties. Based on these data, we recommend the TA, TP, and PL tendons as graft sources for ligamentous reconstruction around the knee.

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