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Effects of Braiding on Tensile Properties of Four-Strand Human Hamstring Tendon Grafts

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Background: Anterior cruciate ligament reconstruction is commonly performed with autogenous hamstring tendon grafts.
Purpose: To ascertain the effects of braiding on ultimate tensile strength and stiffness of hamstring tendon graft.
Study Design: Controlled laboratory study.
Methods: Sixteen fresh-frozen semitendinosus and gracilis tendons were harvested from eight matched (right and left) human cadaveric specimens. Both sets of hamstring tendons from each matched pair were doubled, creating a four-strand graft. Grafts were then randomized so that one graft from each matched pair was braided and the other remained unbraided. The diameter of each graft construct was recorded. Grafts were tested to failure on a materials testing machine.
Results: There were no significant differences in cross-sectional area before or after braiding. Fifteen of 16 tendons failed midsubstance; 1 failed at the lower clamp. Braiding reduced the initial tensile strength and stiffness of human hamstring tendon grafts in this study by 35.0% and 45.8%, respectively.
Conclusions: Braiding may place the collagen fibers in a suboptimal orientation for loading that results in a weaker graft. We do not recommend the use of braiding if the strongest, stiffest initial graft is desired.

Anterior cruciate ligament reconstruction with the use of autogenous hamstring tendon grafts is a well-recognized procedure.[1,2,7] Initially, the semitendinosus and gracilis tendons were harvested and used as two-strand autografts for reconstruction of the deficient ACL, but concerns about strength led to the use of four-strand constructs. Creating a four-strand graft, by folding the tendons in half, decreases the length but increases the tensile strength and stiffness of the graft.[3]

In an attempt to further increase the bulk and strength of hamstring tendon grafts, various investigators have braided the hamstring tendon grafts.[7,8] Although it is clear that braiding changes the orientation of the collagen bundles in the graft tissue and the overall geometry of the graft, it is unclear what effect braiding has on tensile strength. Braiding has qualitative effects on the workability and consistency of the graft.[7]

Although the textile industry has commonly used braiding to improve the flexibility and handling properties of ropes, yarns, and suture, braiding does not improve the strength of the textiles. Hearle et al.[4] demonstrated that there is a decrease in fiber bundle strength with braiding that is proportional to $[\cos(\alpha)]^2$ where α is equal to the twist angle. In a recent study on the effects of braiding in a sheep tendon model, a twist angle of 45° resulted in the predicted decrease in strength of 50%.[5]

To date, however, the effects of braiding on the ultimate tensile strength of human hamstring tendons, such as those used routinely in ACL reconstructions, have not been examined. The purpose of this study was to investigate how braiding affects the stiffness and ultimate tensile strength of four-strand human hamstring tendon grafts.

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MATERIALS AND METHODS

Semitendinosus and gracilis hamstring tendons were harvested from the medial side of eight matched pairs of fresh-frozen human cadaveric knees. Knees with evidence of prior surgery were excluded from the study. The mean age of the specimens was 85 years (range, 71 to 92). Five of the eight matched pairs were from male cadavers and three were from female cadavers. All excess soft tissue was stripped from the tendons. To prevent desiccation, the tendons were moistened and wrapped in saline-soaked gauze sponges. The tendons were then wrapped in aluminum foil, placed in an airtight bag, and stored at –20°C. The tendons were thawed overnight at 4°C and then warmed to room temperature for braiding and mechanical testing.

Both sets of hamstring tendons from each matched pair were folded in half over two No. 5 braided sutures, creating a four-strand graft. Grafts were then randomly divided, with one graft from each matched pair braided and the other left unbraided (Fig. 1). For braided specimens, we used a double-loop weave, as has been used clinically, in which the ends of each tendon (semitendinosus and gracilis) were sutured together to form a closed loop.[7] The two loops (semitendinosus and gracilis) were then woven together from an outward to an inward direction to form a woven four-strand construct. The diameter of each graft construct was recorded. The twist angle was set at 30° to 35°, as has been used clinically.[7]

Pre Hoc Power Analysis

Based on the data from previous published studies,[3,5] a pre hoc power analysis was performed to determine sample size, with the desired level of significance set with an alpha of 0.05 and a beta of 0.80.

Change in Overall Diameter

All grafts were sized to the nearest millimeter before and after braiding by using standard clinical ACL sizing tubes (Acufex, Smith & Nephew Endoscopy, Andover, Massachusetts). The change in diameter was calculated within each specimen by subtracting the postbraided from the prebraided diameter. This method is used clinically to determine graft size. No further attempt was made to determine the precise cross-sectional area or volume.

Mechanical Testing

Mechanical testing was performed with the use of a procedure described by Nicklin et al.[5] Tendon grafts were tested on an MTS 858 Bionix Testing Machine (MTS Systems Corp., Eden Prairie, Minnesota) with a standard gauge length of 25 mm. The tendons were secured in brass grips, which were frozen with liquid CO_2 for a maximum of 2 minutes.[6] Care was taken not to freeze the gauge length (25 mm) of the tendons. The tendons were preconditioned to a distraction of 1 mm for 10 cycles, which was followed by testing to failure at 50 mm/sec, with a data acquisition rate of 1000 Hz. The stiffness (in Newtons per millimeter) for the first 10 cycles was calculated. The stiffness, ultimate load to failure, and the mode of failure were recorded.

Figure 1. Unbraided (left) and braided (right) four-strand hamstring tendon grafts.

Change in Ultimate Load to Failure and Stiffness

The site and the mode of failure were recorded for each specimen. Maximum load was recorded. Stiffness was measured in the linear portion of the elongation curve. Maximum stress was calculated by dividing maximum load by cross-sectional area.

The changes in ultimate tensile load to failure and stiffness were calculated by comparing the braided and unbraided specimens from each matched pair. The formula is outlined as *percent change = 100% – (braided/unbraided × 100%).*

Statistical Analysis

Data were analyzed by using a paired *t*-test with significance set at $P < 0.05$. A one-way analysis of variance was also performed. The ratios of the braided tendons to the contralateral control tendons were also calculated.

RESULTS

With the methods employed, we were unable to detect any statistically significant differences in cross-sectional area either from right to left or before or after braiding. The

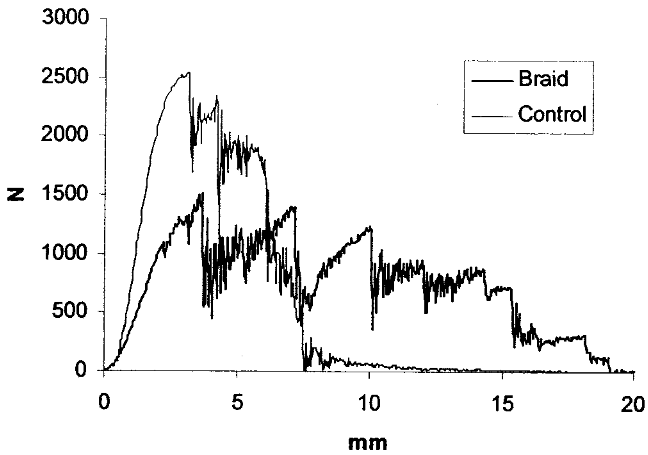

Figure 2. Load displacement curves of braided and unbraided (control) matched hamstring tendons.

mean diameter for the right knees was 8.5 mm (range, 7 to 10) and the mean for the left knees was 8.625 mm (range, 7 to 10). The mean diameter of the braided grafts was 8.625 mm (range, 7 to 10) and that of the unbraided tendon grafts was 8.5 mm (range, 7 to 10). Fifteen of 16 tendon grafts failed at the midsubstance, and 1 specimen failed at the lower clamp because of poor CO_2 uptake during the freezing process. This matched pair was subsequently discarded from the analysis.

The load displacements are summarized in Figure 2. The mean peak load to failure for unbraided tendons was 3404.16 N, whereas the mean peak load to failure for braided tendons was 2223.53 N (Table 1). This represents a 35.0% reduction in ultimate tensile strength with braiding ($P = 0.033$).

The mean stiffness (in Newtons per millimeter) of the braided constructs was also decreased by 45.8% when compared with the four-strand controls (Table 1) ($P = 0.018$).

DISCUSSION

This study addressed the effects of braiding on the initial tensile strength of hamstring tendon grafts and demonstrated a 35.0% reduction in ultimate strength and a 45.8% reduction in stiffness when a clinically applied braiding technique was applied to human tendon specimens. As has been previously elucidated, the use of braiding to strengthen tendon grafts may have been based on an erroneous assumption that braiding is used in the production of cables, ropes, yarns, and sutures to increase strength.[5] Although braiding is used extensively in the manufacture of these products, it is used to improve flexibility and workability, but not strength. Studies by Hearle et al.[4] have shown a decrease in fiber bundle strength that is mathematically related to the angle of the twist. Strength was shown to decrease by the square of the cosine of the twist angle. Braids in the current study had a twist angle of approximately 30° to 35°, which resulted in an approximate 35.0% decrease in strength, as predicted mathematically.

Other authors have examined the biomechanical properties of braided hamstring tendon grafts. Wilson et al.[8] performed a biomechanical analysis of matched bone-patellar tendon-bone and double-looped, braided semitendinosus and gracilis tendon grafts. Biomechanical testing demonstrated that the average load to failure for the patellar tendon grafts was 1784 N, compared with 2422 N for the braided hamstring tendon grafts, a statistically significant difference. There was no statistically significant difference in stiffness between grafts (patellar tendon, 210 N/mm; hamstring tendon, 238 N/mm). The elastic modulus was 225 MPa (±129) for the patellar tendon grafts and 145 MPa (±58) for the hamstring tendon grafts (significantly different). The average cross-sectional area for the hamstring tendon grafts was 57 mm^2, compared with the 45 mm^2 for the patellar tendon grafts. The hamstring tendon grafts were significantly stronger than the matched central-third patellar tendon grafts, but the two grafts were similar in stiffness. The patellar tendon grafts had a higher modulus than the hamstring tendon grafts.

In another study, Hamner et al.[3] found that equally tensioned, multiple-strand hamstring tendon grafts have tensile properties that are higher than those of patellar tendon grafts. The grafts in their study were not braided. They also found that tensioning the grafts affected the ultimate tensile strength, with those tensioned equally having a maximum load to failure of 4590 N, as compared with a mean of 2831 N for those tensioned manually.

Nicklin and colleagues[5] found that braiding sheep extensor tendons resulted in an approximate 50% decrease in the ultimate tensile strength of the tendons. They used the same mechanical testing protocol as in the present study and presented a detailed mathematical analysis that predicted the change in mechanical properties as a function of the cosine of the twist angle. The braided constructs in this study failed in a stepwise fashion, as did those from the sheep. In both studies, the grafts were preconditioned and stress-relaxed starting from a reproducible state.

TABLE 1
Mechanical Testing Data for Braided Tendons Compared with Unbraided Controls

Group	Number	Ultimate tensile strength (N)		Stiffness (N/mm)	
		Mean	SD	Mean	SD
Braid	7	2223.53	1056	843.1	511.3
Control	7	3404.16	922	1553.5	459.5
		P = 0.033		*P = 0.018*	

The current study addressed the effects of braiding on the tensile strength of human hamstring tendon grafts. The clinical implications of this study are of obvious interest to surgeons who perform ACL reconstructions with hamstring tendon grafts. Some surgeons have found braiding to be useful and use the construct in their clinical practices.[7] The current study, however, shows that braiding human tendons decreases the load to failure and the stiffness.

Braiding may place the collagen fibers in a suboptimal orientation for loading that results in a weaker graft because of excessive shear loading between the fascicles. Nevertheless, it is important to note that the peak load to failure with the braided constructs in our study and that of Wilson et al.[8] is still greater than 2000 N, which is still stronger than most patellar tendon grafts.

Although this study answers one question, many others remain. Issues such as the type of braid and the changes that occur as the graft undergoes ligamentization remain unanswered. It remains unclear whether the decreases in tensile strength and stiffness that the current study demonstrates are clinically relevant. Nevertheless, our recommendation, based on data from this biomechanical study, is to avoid the use of braiding if the strongest, stiffest initial graft construct is desired.

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