

Hamstring Graft Prepared With Suture Tape Is Effective in Anterior Cruciate Ligament Reconstruction: A Biomechanical Analysis



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Purpose: To investigate the graft diameters and mechanical properties of hamstring tendons sutured using different materials and techniques. **Methods:** This study used 30 fresh, frozen human cadaveric semitendinosus tendons; the free ends of 10 specimens each were sutured by 2 No. 3 braided polyester sutures with the Krackow technique (BP group), SutureTape with the Krackow technique (ST group), or SutureTape Loop with the locking SpeedWhip technique (SL group). First, the changes in graft diameter from before suturing to after suturing were investigated. Each graft was pre-tensioned to 100 N for 3 cycles and then cyclically loaded to 200 N for 200 cycles. Elongation after cyclic loading and displacement in the 200th cycle were calculated. Finally, each specimen was loaded to failure. The ultimate failure load and stiffness were analyzed. These mechanical properties were statistically analyzed using 1-way analysis of variance. The level of statistical significance was set at $P < .05$. **Results:** In the BP group, the changes in graft diameter were significantly larger than those in the ST and SL groups ($P = .001$). The elongation values after 200 cycles in the BP and ST groups were 3.1 ± 2.0 mm and 5.9 ± 3.4 mm, respectively. In the SL group, elongation (7.7 ± 3.6 mm) was significantly larger compared with that in the BP group ($P = .037$). In contrast, displacement in the 200th cycle was significantly smaller in the ST and SL groups compared with the BP group ($P = .017$). No statistically significant difference was evident for the ultimate failure loads among the 3 groups ($P = .543$). **Conclusions:** The results of this study suggest that SutureTape may be an appropriate option for preparing the hamstring graft in anatomic anterior cruciate ligament (ACL) reconstruction. **Clinical Relevance:** This biomechanical study shows the effectiveness of SutureTape in ACL graft preparation. Clinically, SutureTape may be of benefit in single- or double-bundle ACL reconstruction.

Secure soft-tissue fixation is essential to ligament reconstruction. Therefore, surgeons have several options of using different suture techniques and materials. The Krackow locking stitch has been reported as a superior method for suture fixation of soft-tissue grafts

in a biomechanical study.¹ McKeon et al.² reported that the peak load to failure and elongation were essentially the same, regardless of the number of locking loops. Recently, strong sutures and stitching methods for soft tissues have been developed.^{3,4} Outcomes achieved with elongation of soft tissue fixed with No. 2 Fiber-Loop (Arthrex) by the locking SpeedWhip technique (Arthrex) were similar to those with the Krackow suture technique after testing by cyclic loading.^{4,5} One of the newly developed suture materials is SutureTape (Arthrex), which consists of a high-tensile strength, nonabsorbable, polyblend core. In a biomechanical study, SutureTape had a significantly greater maximum load at failure than high-tensile strength suture in Krackow stitch models.³ Furthermore, a biomechanical study using human cadaveric tendons with suturing by the Krackow technique revealed that SutureTape had a significantly higher failure load than a high-tensile strength, nonabsorbable, polyblend suture.³

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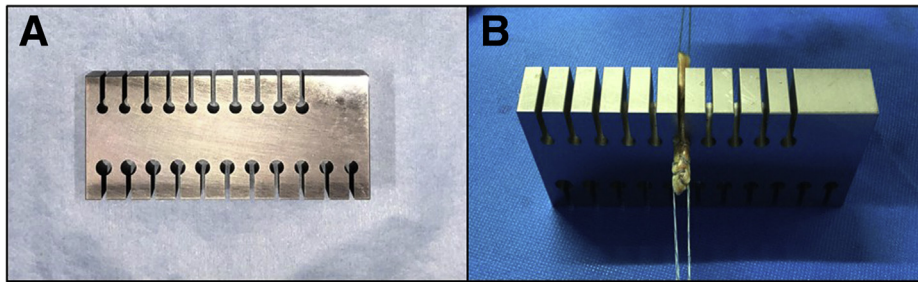


Fig 1. A custom instrument was created to measure the graft diameter. (A) Holes at 0.1-mm increments with a length of 20 mm were made in a stainless steel block. (B) The maximum wedge capable of passing through the hole was defined as the graft diameter.

Anatomic anterior cruciate ligament (ACL) reconstruction with medial hamstring tendon autograft is widely performed by orthopaedic surgeons.^{6,7} For this approach, harvested tendons are looped and nonabsorbable sutures are placed in the free end of the graft.^{8,9} The loop end of the graft is then fixed on the femur, and nonabsorbable sutures are connected to the tibia.¹⁰ The diameters of the femoral and tibial tunnels are decided in reference to graft thickness during anatomic ACL reconstruction.⁸ For the ACL, the average tibial footprint area is

reported to be $114 \pm 36 \text{ mm}^2$; the average width, $10 \pm 2 \text{ mm}$; and the average length, $14 \pm 2 \text{ mm}$.¹¹ The ACL fibers insert firmly and are broadly attached at the region anterior to the anterior horn of the lateral meniscus.¹² Therefore, if the diameter of the tibial tunnels is larger than the actual size of the ACL footprint, there is a risk of breaking the anterior horn of the lateral meniscus.¹³

In some cases of anatomic ACL reconstruction, the diameter of the tibial tunnel is larger than that of the

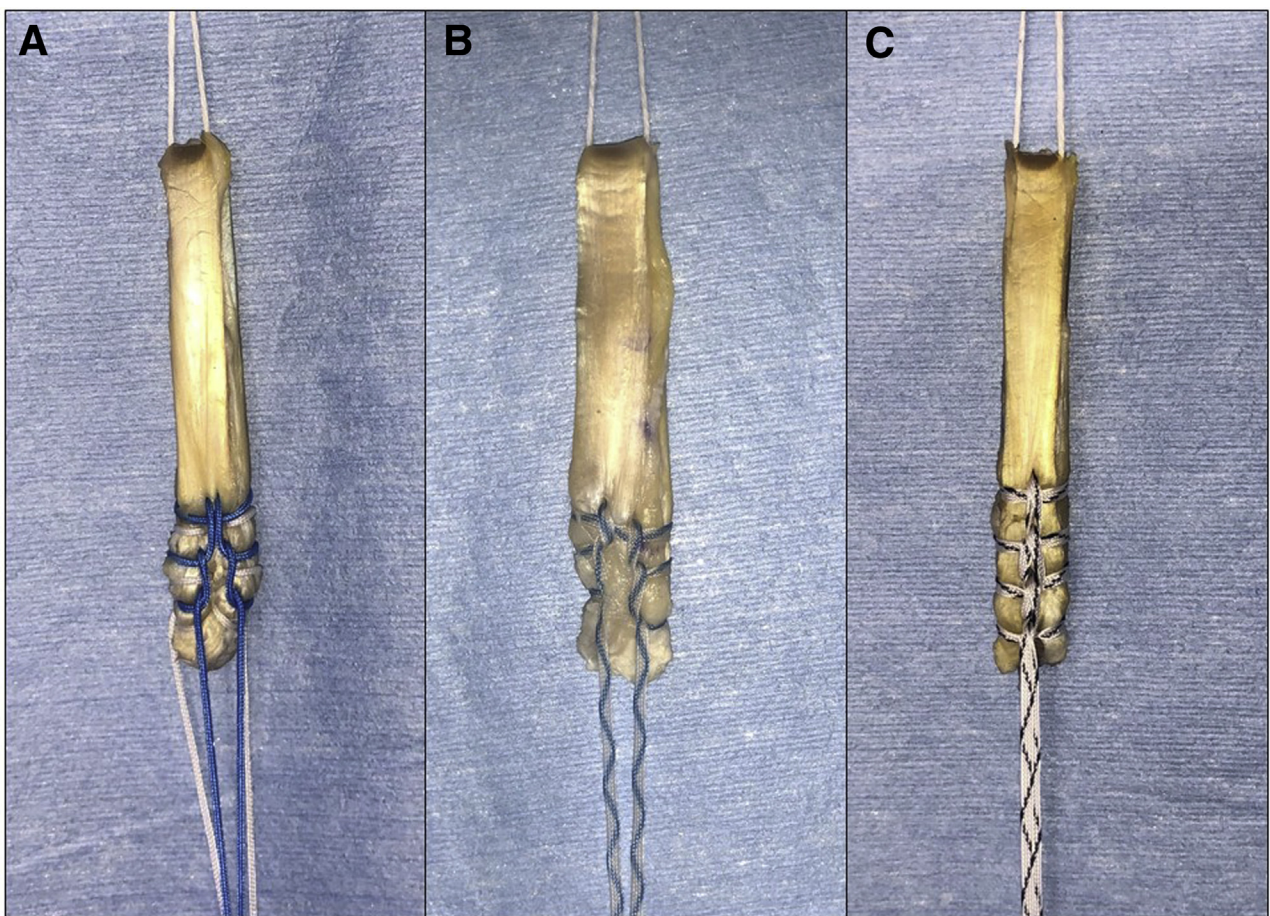


Fig 2. The free ends of the tendon were fixed by 3 methods: Krackow technique with 2 No. 3 braided polyester sutures (BP group) (A); Krackow technique with SutureTape (ST group) (B); and locking SpeedWhip stitch technique with SutureTape Loop (SL group) (C).

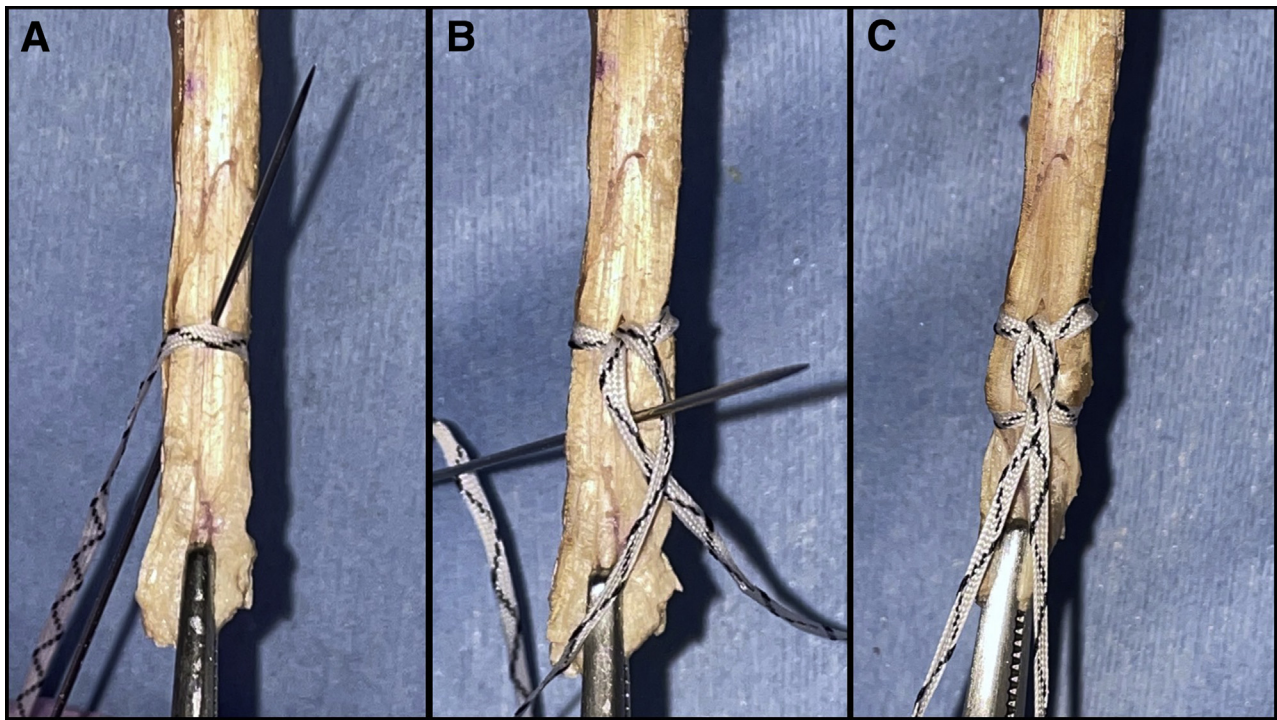


Fig 3. Locked SpeedWhip stitch technique. (A) The needle was passed from back to front. (B) Each strand of the loop was crossed with the tip of the needle. (C) The needle was pulled through the tendon, creating the locking effect.

femoral tunnel because of the thickness of the sutures. However, the diameter changes in the hamstring tendon graft after various suture techniques have not been investigated. Furthermore, the mechanical properties of hamstring tendon fixed using a SutureTape Loop (Arthrex) with the locking SpeedWhip technique have not been clarified. The purpose of this study was to investigate the graft diameters and mechanical properties of hamstring tendons sutured using different materials and techniques. The hypothesis was that the change in graft diameter would be comparatively smaller in cases using SutureTape. Consequently, the mechanical properties of hamstring tendons fixed using SutureTape and SutureTape Loop would be essentially the same, despite the use of different suture techniques (Krackow technique and locking SpeedWhip technique, respectively).

Methods

For this study, we used 30 fresh, frozen human cadaveric semitendinosus tendons donated to the anatomy department of our university. The mean age at the time of death was 82.3 years (range, 74-93 years). The specimens were stored at -20°C and thawed for 24 hours at room temperature before testing. Each tendon was cut from the distal end to a length of 11 cm. No degenerative or pathologic changes were found in any tendon. The graft diameter was

calculated by a custom instrument created by us specifically for this study, by which holes at 0.1-mm increments along a length of 20 mm were made in a stainless steel block. The maximum size of the wedge capable of passing through the hole was defined as the graft diameter (Fig 1). Measurements of graft diameter were performed by a single examiner (T.K.). The changes in graft diameter from before suturing to after suturing were analyzed. This study was approved by the ethics committee of our institution.

Suture Techniques

The free ends of 10 specimens each were sutured using 3 different methods by randomized selection. In the braided polyester group (BP group), specimens were fixed with 2 No. 3 braided polyester sutures (ELP; Akiyama Seisakusyo). On the basis of previous biomechanical findings,^{1,2} we created the free end of the hamstring tendon graft using 2 No. 3 braided polyester sutures with the Krackow method.⁹ Suturing was performed using a 3-loop Krackow pattern with evenly spaced loops at 2 and 3 cm from the free end of the tendon. Two nonabsorbable stitches were used because semitendinosus tendons sutured by a single No. 3 braided polyester suture failed during cyclic loading examination in a pilot study. In the SutureTape group (ST group), specimens were fixed with 1.3-mm SutureTape in 3 locking loops by the Krackow technique. In the SutureTape Loop group (SL group), specimens were



Fig 4. The specimen was mounted on a universal material testing machine. The free strands of suture were tied to a hook 20 mm from the tendon end.

fixed with 1.3-mm SutureTape Loop in 4 locking loops by the locked SpeedWhip stitch (Fig 2). The needle was passed from back to front. Then, each strand of the loop was crossed with the tip of the needle, and the needle was pulled through the tendon, creating the locking effect (Fig 3).

Biomechanical Testing

A universal material testing machine (AG-I; Shimadzu) was used to conduct biomechanical testing. The loop ends of the graft were placed in a hook below the material testing device. Then, the free strands of suture were tied to a hook 20 mm from the tendon end (Fig 4). A 6-throw square knot was performed to secure the suture.⁴ A blue line was marked on the graft 5 cm from the free end of the tendon. Blue dots were also made on the suture limb to visualize the absence of knot slippage.¹⁴ Each specimen was pre-tensioned from 0 to 100 N at 100 mm/min for 3 test cycles, which clinically simulated the removal of slack tension.⁴ The change after pre-tensioning was subtracted from elongation during cyclic or failure testing. Next, cyclic loading with

200 cycles from 0 to 200 N was applied to the specimens. The displacement velocity was set at 200 mm/min. This condition simulated the force on the ACL during level walking.^{15,16} These parameters have also been used in previous studies.^{1,4} A video digitizing system (GZ-MG575-S; Victor) was used to record the motion of the graft during cyclic load testing. Image analysis software (ImageJ, version 1.53a; National Institutes of Health) was used to measure the distance between the marker of the suture limb and the 5-cm blue line from the end of the tendon.

Elongation of the suture-tendon construct after cyclic loading with 200 cycles was assessed by calculating the difference in the distance between the blue line on the tendon and the marker of the suture limb. The length of the suture-tendon construct with 0 N and 200 N in the 200th cycle was also measured using the video digitizing system (Fig 5). Displacement in the 200th cycle was determined as the change in the length of the suture-tendon construct during the 200th cycle. After 200 cycles, the percentages of elongation and displacement were calculated based on the initial distance between the digitizing markers of the tendon and suture limb. After cyclic loading, each specimen was loaded to failure at 20 mm/min. Failure modes, such as suture breakage, suture pullout, or tendon breakage, were also recorded by the video digitizing system. During failure testing, elongation was recorded at 20 Hz using software (Trapezium; Shimadzu) connected to the material testing machine. Stiffness was also calculated from the linear region of the load-elongation curve in failure testing.

Statistical Analysis

The sample size was calculated based on elongation after cyclic loading in the pilot study. Power analysis (power, 0.8; α , .05; detectable difference, 12.0; standard deviation, 9.0) indicated a sample size requirement of 10 per group. Statistical analysis was conducted with EZR (Saitama Medical Center, Jichi Medical University), which is a graphical user interface for R (version 2.13.0; R Foundation for Statistical Computing).¹⁷

Change in graft diameter, elongation after pre-tensioning and cyclic loading, displacement in the 200th cycle, ultimate failure load, and stiffness were statistically analyzed using 1-way analysis of variance. The Tukey-Kramer post hoc test was also performed. The level of statistical significance was set at $P < .05$.

Results

Changes in graft diameter from before suturing to after suturing are listed in Table 1. In the BP group, the mean change in graft diameter was 0.9 ± 0.3 mm, which was significantly larger than that in the ST and SL groups ($P < .001$).

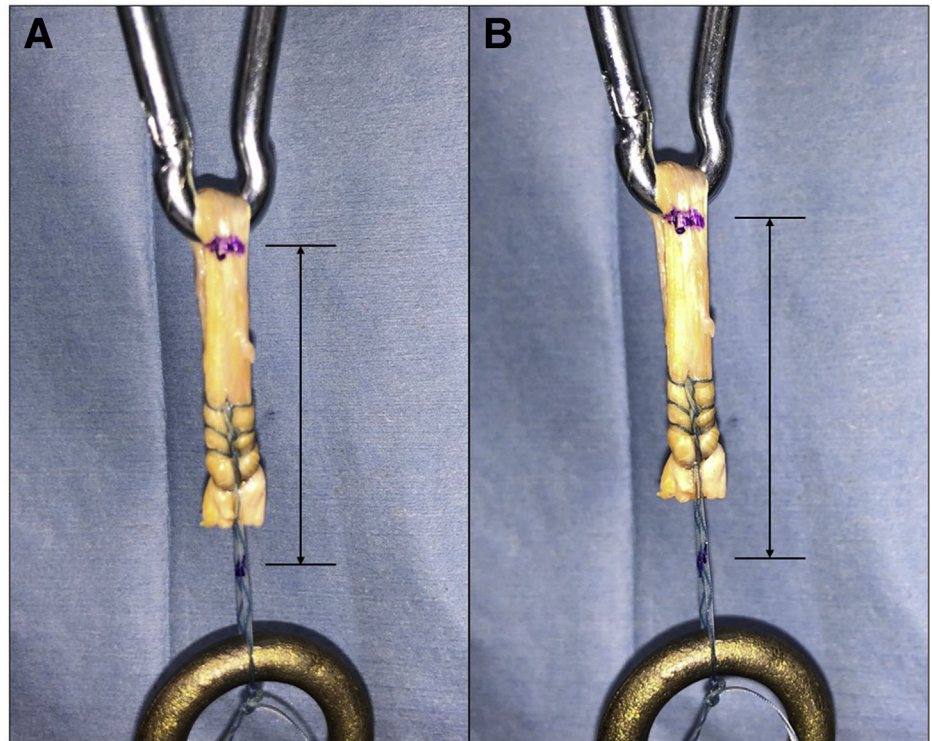


Fig 5. Length of suture-tendon construct (*arrows*) by applying 0 N in 200th cycle (A) and 200 N in 200th cycle (B). Displacement in the 200th cycle was determined as the difference in these lengths.

The mean elongation values after cyclic loading in the BP and ST groups were 3.1 ± 2.0 mm ($7.5\% \pm 5.0\%$) and 5.9 ± 3.4 mm ($13.1\% \pm 8.2\%$), respectively (Table 2). In the SL group (7.7 ± 3.6 mm, $16.3\% \pm 8.3\%$), elongation was significantly larger compared with the BP group ($P = .037$). In contrast, mean displacement of each graft in the 200th cycle was 1.8 ± 0.8 mm ($4.5\% \pm 1.3\%$) in the BP group, 1.3 ± 0.6 mm ($2.9\% \pm 1.2\%$) in the ST group, and 1.5 ± 0.9 mm ($3.0\% \pm 1.4\%$) in the SL group (Table 2). This value in the BP group was statistically larger than the values in the ST and SL groups ($P = .017$).

Mean ultimate failure load was 437.2 ± 58.1 N in the BP group, 416.0 ± 46.8 N in the ST group, and 411.2 ± 59.9 N in the SL group (Table 3). There was no statistically significant difference among the 3 groups ($P = .543$). Mean stiffness in the BP group was 59.6 ± 6.0 N/mm. This value was significantly smaller than the

values in the ST group (86.2 ± 11.4 N/mm) and SL group (87.0 ± 14.2 N/mm). Tendon breaks at the locking loops of suturing presented in 5 specimens in the ST group and 2 specimens in the SL group. Suture breakages within 1 cm of the graft end occurred in all specimens in the BP group, as well as the remaining specimens in the ST and SL groups, during failure testing.

Discussion

The most important finding of this study was that the changes in graft diameter in the ST and SL groups were significantly smaller than those in the BP group. The tape sutures were able to be pressed down as a flat surface, which may allow a smaller change in graft diameter by enfolding the tendon and could also reduce the mismatch between the femoral and tibial tunnel diameters. Despite anatomic double-bundle ACL

Table 1. Graft Diameter Results Before and After Suturing

| | Before Suturing, mm | After Suturing, mm | Change From before Suturing to after Suturing, mm |
|----------|---------------------|--------------------|---|
| BP group | 5.2 ± 0.5 | 6.1 ± 0.3 | $0.9 \pm 0.3^{*\dagger}$ |
| ST group | 5.3 ± 0.4 | 5.8 ± 0.4 | $0.4 \pm 0.1^*$ |
| SL group | 5.3 ± 0.6 | 5.8 ± 0.5 | $0.5 \pm 0.2^\dagger$ |
| P value | .763 | .217 | <.001 |

NOTE. Data are presented as mean \pm standard deviation.

BP, braided polyester; SL, SutureTape Loop; ST, SutureTape.

*Significant difference between BP and ST groups via Tukey-Kramer test.

†Significant difference between BP and SL groups via Tukey-Kramer test.

Table 2. Results of Mean Graft Elongation After Cyclic Loading Test and Displacement in 200th Cycle

| | Elongation after Cyclic Loading, mm (%) | Displacement in 200th Cycle, mm (%) |
|----------|---|-------------------------------------|
| BP group | 3.1 ± 2.0 (7.5 ± 5.0)* | 1.8 ± 0.8 (4.5 ± 1.3)* [†] |
| ST group | 5.9 ± 3.4 (13.1 ± 8.2) | 1.3 ± 0.6 (2.9 ± 1.2) [†] |
| SL group | 7.7 ± 3.6 (16.3 ± 8.3)* | 1.5 ± 0.9 (3.0 ± 1.4)* |
| P value | .037 | .017 |

NOTE. Data are presented as mean ± standard deviation.

BP, braided polyester; SL, SutureTape Loop; ST, SutureTape.

*Significant difference between BP and SL groups via Tukey-Kramer test.

[†]Significant difference between BP and ST groups via Tukey-Kramer test.

reconstruction, the excessively large diameter of the tibial tunnel broke the anterior horn of the lateral meniscus.¹³ The results of our study suggest that tape sutures are suitable for hamstring graft preparation owing to their ability to minimize the changes in graft diameter.

This study evaluated the biomechanical properties of the double-looped semitendinosus tendon by applying cyclic loading. In previous reports, similar elongations were found between the modified Krackow stitch and the modified SpeedWhip stitch using No. 2 FiberWire (Arthrex).⁴ The results of our study also showed that there were no statistically significant differences between the ST and SL groups regarding elongation after cyclic loading. These results suggest that SutureTape may be used for various suturing methods.

In the BP group, elongation after 200 cycles was significantly smaller compared with the SL group. However, displacement in the 200th cycle yielded significantly larger values compared with the other 2 groups. Graft-tunnel motion was reportedly observed in all patients during treadmill walking at 6 weeks after ACL reconstruction.¹⁸ If excessive graft slippages inside the tunnel were to appear, then bone-tendon healing may be delayed. In the case of hamstring graft prepared by fixation with 2 No. 3 braided polyester sutures, the findings suggest that early excessive exercise should be avoided.

SutureTape has been used to provide ligament augmentation in general.^{19,20} In contrast, SutureTape has recently been used as a tendon fixation instrument. In a biomechanical study, high-tensile strength tape performed with a significantly greater load at failure using the locking SpeedWhip stitch and the Krackow stitch compared with high-tensile strength sutures during a single load to failure.³ In our study, elongation of the hamstring tendon sutured by SutureTape was investigated after cyclic loading. The results indicated that SutureTape was also useful to prepare the hamstring autograft for anatomic ACL reconstruction.

This study used double-looped hamstring tendons harvested from human, fresh, frozen, cadaveric knees. Most of the previous biomechanical studies used either flexor or Achilles tendons in an animal model.^{1-5,14} Previous studies reported that the maximum failure

load and the area of the semitendinosus tendon were $1,216 \pm 50$ N and 14.0 ± 0.5 mm², respectively.²¹ The mechanical properties of porcine flexor profundus tendons and Achilles tendons may differ from those of human, fresh, frozen, cadaveric specimens.^{2,14} Therefore, the results of our study provide surgeons with more useful information for preparation of hamstring graft in the case of anatomic double-bundle ACL reconstruction.

Limitations

This study has several limitations. First, it did not investigate any physiological effects of using each material. Bone-tendon healing and vascularization occur in living tissues just after surgery. Second, the biomechanical study was performed using human, fresh, frozen, cadaveric specimens, which is a different setting than in vivo testing; however, the study simulated early range of motion and level walking, and the results discovered for these mechanical properties may contribute to an understanding of physical therapy after anatomic ACL reconstruction using hamstring tendons. Third, the mean age of the specimen was 82.3 years. Most patients who undergo this operation are younger athletes. These results may not precisely represent the situation of hamstring autograft in anatomic ACL reconstruction. Fourth, the graft diameter was measured by a single examiner, and testing was performed only once. In the pilot study, no differences in the measured graft diameter occurred among 3 inspectors. To prevent the deterioration of the specimens,

Table 3. Biomechanical Properties During Load-to-Failure Test

| | Ultimate Tensile Load, N | Stiffness, N/mm |
|----------|--------------------------|--------------------------|
| BP group | 437.2 ± 58.1 | 59.6 ± 6.0* [†] |
| ST group | 416.0 ± 46.8 | 86.2 ± 11.4* |
| SL group | 411.2 ± 59.9 | 87.0 ± 14.2 [†] |
| P value | .543 | <.001 |

NOTE. Data are presented as mean ± standard deviation.

BP, braided polyester; SL, SutureTape Loop; ST, SutureTape.

*Significant difference between BP and ST groups via Tukey-Kramer test.

[†]Significant difference between BP and SL groups via Tukey-Kramer test.

the time for calculation was reduced in this study. Fifth, the study did not investigate the mechanical properties of the hamstring graft fixed with a single No. 3 braided polyester suture because in the pilot study, all of the hamstring grafts sutured by a single No. 3 braided polyester suture failed during the cyclic loading test. Therefore, No. 3 braided polyester suture should not be used alone for clinical preparation of the hamstring graft.

Conclusions

The results of this study suggest that SutureTape may be an appropriate option for preparing the hamstring graft in anatomic ACL reconstruction.

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