Continuous-Loop Tape Technique Has Greater Stiffness and Less Elongation Compared With Tied-Suture Fixation of Full-Thickness All–Soft Tissue Quadriceps Tendon Autografts

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Background: Many graft fixation techniques are utilized for full-thickness soft tissue quadriceps tendon autografts during anterior cruciate ligament reconstruction (ACLR).

Purpose: To determine the tensile properties of all–soft tissue quadriceps tendon graft fixation using a tied-suture versus continuous-loop tape technique. It was hypothesized that the continuous-loop tape technique would have less cyclic elongation and greater ultimate load to failure and stiffness compared with a commonly used tied-suture technique.

Study Design: Controlled laboratory study.

Methods: Sixteen fresh-frozen human knee specimens were used to harvest a full-thickness all–soft tissue quadriceps tendon graft; half were secured using a Krackow suture technique with 2 braided sutures, and half were secured using a continuous-loop tape suspensory fixation button with a rip-stop stitch. Cyclic and permanent elongation, toe- and linear-region stiffness, and ultimate load were determined. Statistical analysis was performed at $P < .05$.

Results: The tied-suture fixation group demonstrated significantly higher permanent elongation (11.7 ± 3.6 vs 4.2 ± 1.0 mm, $P < .001$) and cyclic elongation (5.9 ± 1.3 vs 2.0 ± 0.4 mm, $P < .001$) compared with the continuous-loop tape fixation group. There was a significantly higher linear-region stiffness with continuous-loop tape fixation compared with tied-suture fixation (98.8 ± 12.7 vs 85.5 ± 7.5 N/mm, $P = .022$). No significant difference in ultimate load between groups (517.1 ± 149.2 vs 465.6 ± 64.6 N) was found. The mode of failure was tendon pull-through for the continuous-loop tape group and suture breakage in the tied-suture group ($P < .001$).

Conclusion: Continuous-loop tape fixation is superior to tied-suture fixation in regard to elongation and stiffness for all–soft tissue quadriceps tendon grafts, but there was no significant difference in ultimate load.

Clinical Relevance: Continuous-loop tape fixation of all–soft tissue quadriceps tendon grafts for ACLR is a valid technique with superior tensile properties.

Keywords: ACL; quadriceps tendon; graft fixation; biomechanics

While graft selection in anterior cruciate ligament (ACL) reconstruction (ACLR) continues to be a topic of debate, quadriceps tendon autografts have been increasingly chosen. This is because of a reported reduced incidence of anterior knee pain[8] and improved postoperative rotatory knee instability, as measured by fewer positive pivot-shift tests when compared with bone–patellar tendon–bone constructs,[15] currently the most commonly used graft in the United States.[17] The fixation site is considered to be the mechanically weakest link in the immediate postoperative period after ACLR and therefore plays an important role in preventing recurrent instability.[14] With the increasing use of quadriceps tendon autografts in ACLR, surgeons have the choice between many fixation techniques for all–soft tissue quadriceps tendon grafts.

Frequently, all–soft tissue quadriceps tendon grafts are prepared using suture fixation techniques, with the suture

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being the weakest point.[10,16,27] As an alternative to tied suspensory fixation, adjustable loop devices have been introduced as a possible option for graft fixation, but there are concerns that adjustable-loop constructs may elongate with cyclic loading.[5,7] Furthermore, mechanical tests of fixation devices without tissue in the testing construct have demonstrated significantly less displacement and greater stiffness and ultimate load favoring continuous-loop devices rather than adjustable-loop devices, although retensioning and knot-tying may reduce concerns of knot slippage seen with adjustable-loop devices.[12,21,26]

Although no differences in clinical outcomes between continuous-loop and adjustable-loop fixation have been demonstrated, previous work has demonstrated that continuous-loop devices are reasonable alternatives for the fixation of flexor tendon grafts in double-bundle ACLR.[18,23] Operative efficiency and fixation security could be improved if continuous-loop tape devices could be applied to all–soft tissue quadriceps tendon grafts for ACLR.[11,13] Continuous-loop tape fixation for all–soft tissue tendon-only grafts may decrease operative time, maximize the strength of fixation, and prevent early failure in ACLR. Continuous-loop tape fixation may be biomechanically advantageous as it is substantially thicker than a braided suture; however, because the continuous-loop tape device passes through the graft at only 1 point, it may create a stress riser, leading to construct failure by pullout through the substance of the graft. Therefore, their tensile properties should be evaluated when using a continuous-loop tape device for fixation of all–soft tissue quadriceps tendon grafts.

The purpose of this study was to compare ultimate load, stiffness, and elongation between application of the closed-loop tape fixation technique of all–soft tissue quadriceps tendon grafts and a commonly used simple tied suture. It was hypothesized that continuous-loop tape fixation of all–soft tissue quadriceps tendon grafts would have less cyclic and permanent elongation and greater ultimate load and stiffness compared with a currently used tied-suture fixation technique.

METHODS

In this study, 16 quadriceps tendons were harvested from fresh-frozen human cadaveric knee specimens (7 female and 9 male specimens; age, 60.8 ± 19.5 years [range, 24-92 years]).[3] Prior approval was obtained by the Committee for Oversight of Research and Clinical Training Involving Decedents at the University of Pittsburgh for the use of cadaveric knee specimens. Specimens were obtained from tissue banks approved by the University of Pittsburgh's Office for Oversite of Anatomic Specimens from cadavers with no history of knee injuries or surgeries. Limited medical history was available for cadaveric specimens, reducing the ability of graft donors to be screened for comorbid medical conditions that might alter the mechanical properties of the harvested grafts.

Grafts were stored at –20° C before testing, thawed for 24 hours, and allowed to come to room temperature. Before graft harvest, all quadriceps tendons were visually inspected to ensure there were no defects or scar formation. All grafts were harvested as a 10 mm–wide full-thickness graft. Before suture fixation, the length of the grafts was recorded using a metric caliper accurate to 0.1 mm. The width of the grafts was also measured using the metric caliper at 3 points along the graft length (one-quarter, one-half, and three-quarters of the distance between the patellar harvest site and musculotendinous junction), and the mean thickness was calculated. The mean graft length of the specimens was 71.3 ± 8.7 mm (range, 59.2-90.0 mm), and the mean graft thickness was 5.7 ± 0.9 mm (range, 4.4-7.5 mm).

Eight grafts were fixed using a suture technique at the patellar end of the graft using 2 No. 2 Ultrabraid sutures (Smith & Nephew) in a Krackow stitch configuration.[16] A Krackow stitch was chosen because it has been shown to have greater ultimate load compared with whipstitch and baseball stitch configurations as a result of its ability to prevent suture pullout.[16] Stitches were placed at regular intervals approximately 5 mm apart,[9] extending 15 mm along the length of the graft as previously described (Figure 1A).[28] Sutures were passed through a suspensory fixation button (EndoButton; Smith & Nephew) and secured at a length of 20 mm from the patellar end of the graft, making the length from suture to button a total of 35 mm. A single knot was tied with 1 tail from each suture on either side of the graft passed together to form 1 limb of the knot. In this manner, the knot consisted of 4 separate suture tails from 2 strands of suture. For the preparation of the continuous-loop tape fixation, the remaining 8 grafts had a figure-of-8 locking stitch placed 15 mm from the patellar end of the graft. A blunt dilator was used to widen a 2-mm hole below the level of the locking stitch, and a suture-passing device was used to pull the continuous-loop tape fixation device (EndoButton BTB CL 35 mm; Smith & Nephew) through the graft (Figure 1B). The

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Ethical approval for this study was obtained from the University of Pittsburgh Committee for Oversight of Research and Clinical Training Involving Decedents (study No. 501).

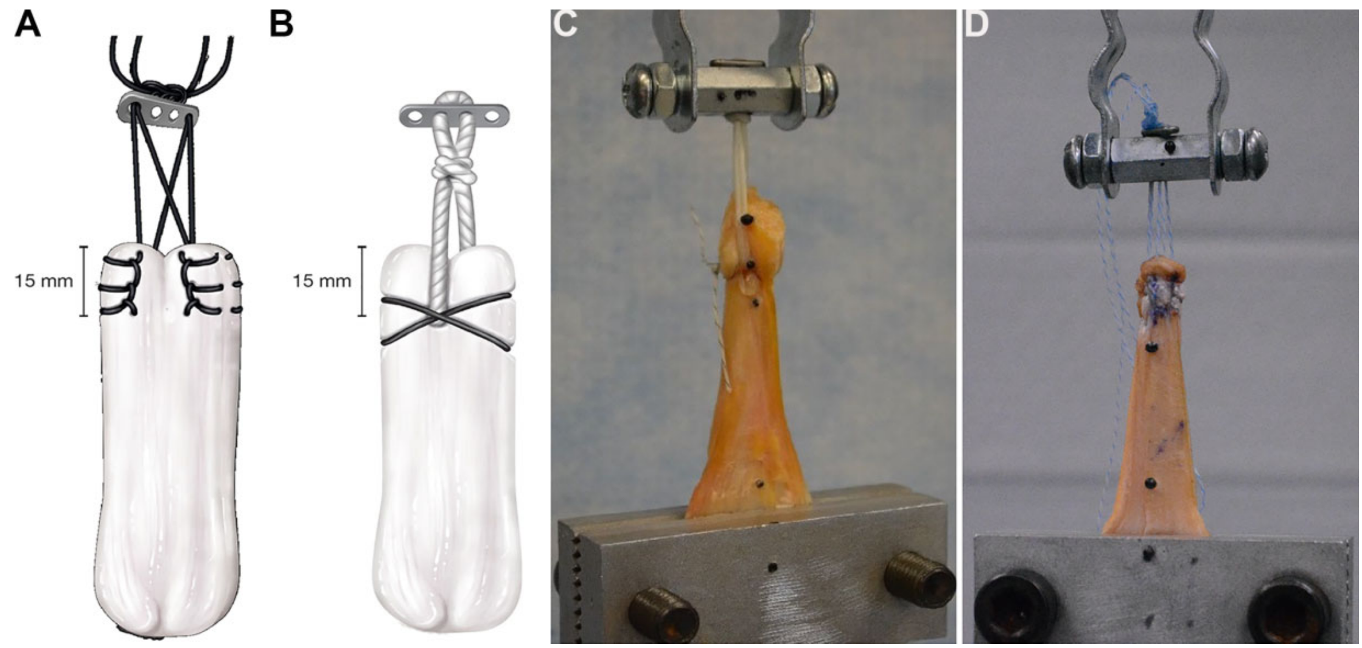

Figure 1. Graft preparation of all–soft tissue quadriceps tendon graft including (A) tied-suture fixation and (B) continuous-loop tape fixation performed on the patellar end of the graft. (C and D) The graft was placed on a custom jig with the quadriceps end in the bottom clamp and the patellar end with either the tied-suture or continuous-loop tape fixation placed through the custom jig. Tracking markers (black dots) were affixed to the specimen with cyanoacrylate.[19] The gauge length was used to measure the total length of the construct. The digital motion tracking markers were used to assess changes in length at the different portions of the construct between each set of markers during the loading protocol. Markers were placed on each clamp at each end of the quadriceps tendon graft, adjacent to the site of fixation, on the specialized clamp, and custom jig. Measurements of elongation were made in the fixation construct, in the substance of the tendon, and between the tendon and the specialized soft tissue clamp; this allowed us to determine which portion of the construct was elongating and detect any slippage between the clamps.

continuous-loop tape fixation device was looped over the fixation button and secured upon itself.

Grafts were mounted on a uniaxial materials testing machine (model 5965; Instron) with the quadriceps end clamped and the cortical fixation device passed through a custom mount (Figure 1C). This uniaxial materials testing machine has been previously determined to be accurate to ±0.1 mm for position and ±5 N for applied force.[19] A custom clamp was securely tightened to the graft to prevent graft slippage. Digital motion tracking markers in the form of optical tracking markers with a video-analysis system (Spica Technology; 0.01-mm accuracy) were placed on the lower clamp, on the specimen, and on the custom mount to ensure <1 mm of slippage occurred between the ligament and distal clamp during the testing process.[19] No tested specimens had clamp slippage.

All grafts were tested under the same loading conditions (Figure 2), and saline was applied to the graft tissue at 10-minute intervals to prevent desiccation. All loading was performed at 10 mm/min, which is on the same order of magnitude of previous studies that have examined the structural properties of graft fixation techniques.[6,24,25,33] Grafts underwent preloading to 3 N to remove laxity within the system while allowing for analysis of structural properties within the toe region during biomechanical testing. Preconditioning was performed for 20 cycles between 3 and

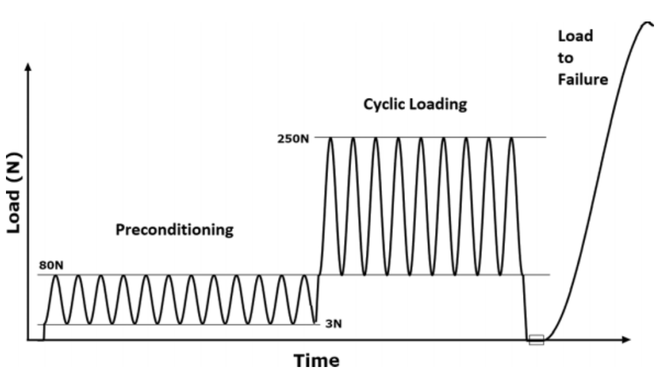

Figure 2. Actual protocol for mechanical testing of all–soft tissue quadriceps tendon autograft using a tied-suture or continuous-loop tape fixation technique. This is neither a simulated nor real case used for data collection.

80 N based on normal ACL graft tension in vivo.[20,22] Cyclic loading for 100 cycles was performed between 80 and 250 N, between normal ACL graft tensioning and the estimated force seen within the ACL during normal gait.[22,29] Graft tissue was allowed to recover under no strain for 1 hour between cyclic loading and loading to failure. Finally, a load-to-failure test was performed.

TABLE 1
Tensile Properties for the Continuous-Loop Tape and Tied-Suture Fixation Techniques.[a]

Variable	Continuous-Loop Tape Fixation	Tied-Suture Fixation	*P* Value
Toe-region stiffness, N/mm	18.9 ± 4.7 (13.5-26.4)	21.1 ± 7.0 (10.0-29.3)	.477
Linear-region stiffness, N/mm	98.8 ± 12.7 (73.0-112.2)	85.5 ± 7.5 (77.4-101.6)	**.022**
Permanent elongation, mm	4.2 ± 1.0 (2.8-6.0)	11.7 ± 3.6 (6.9-17.1)	**<.001**
Cyclic elongation, mm	2.0 ± 0.4 (1.0-2.3)	5.9 ± 1.3 (4.0-8.0)	**<.001**
Ultimate load, N	517.1 ± 149.2 (361.5-730.6)	465.6 ± 64.6 (343.3-544.6)	.392

[a]Data are presented as mean ± SD (range). Bolded *P* values indicate statistically significant differences between groups ($P < .05$).

Structural properties were calculated, including cyclic and permanent elongation, toe-region stiffness, linear-region stiffness, and ultimate load. Cyclic elongation was defined as the difference in gauge length at 250 N of the first cycle and 250 N of the final cycle during cyclic loading. Permanent elongation was defined as the difference in gauge length at 80 N during the first cycle of cyclic elongation and the gauge length at 80 N during load-to-failure testing. Toe-region stiffness was defined by adding and removing maximum and minimum points along the start of the load-to-failure curve until R^2 <0.99 was achieved. Linear-region stiffness was defined by removing maximum and minimum points along the linear portion of the load-to-failure curve until a linear fit R^2 >0.99 was obtained. Finally, the mode of failure was observed and recorded for each specimen.

Using preliminary testing data, a 2-tailed a priori power analysis was performed to determine the necessary sample size with power ($1 - \beta$) of 0.80 and significance of 0.05 (G* Power Version 3.1; Heinrich-Heine-Universität Düsseldorf). The power analysis indicated that 5 grafts per group would be required to show a significant difference in ultimate load between groups. Based on preliminary testing data, the delta value for the power analysis was 123 N. Categorical variables were compared using the Fisher exact test. The independent-samples *t* test was used to compare all normally distributed data, while the Mann-Whitney *U* test was used for nonnormally distributed data (SPSS Version 26; IBM). All values are presented as mean ± standard deviation unless otherwise noted. Statistical significance was set at $P < .05$ for all statistical analyses.

RESULTS

There were no significant differences in age, sex, laterality, and graft width, thickness, or length between the continuous-loop tape and tied-suture fixation groups. With regard to the tensile properties of each fixation technique (Table 1), the linear-region stiffness was 16% greater with continuous-loop tape fixation compared with tied-suture fixation, but there was no significant difference in toe-region stiffness between the 2 groups. Permanent and cyclic elongations were 2.8 and 3.0 times greater for the tied-suture group compared with the continuous-loop tape group. There was no significant difference in ultimate load between the 2 groups.

The graft fixation techniques demonstrated a clear distinction in the mode of failure between the 2 groups. For all specimens fixed with the continuous-loop tape fixation method, the construct failure mode was tendon pull-through, with the continuous-loop tape device pulling through the end of the graft longitudinally in line with the graft fibers. For all specimens in the tied-suture fixation group, the mode of failure was suture breakage ($P < .001$).

DISCUSSION

The most important finding of this study was that continuous-loop tape fixation of all–soft tissue quadriceps tendon grafts resulted in less permanent and cyclic elongation than did tied-suture fixation. Additionally, linear-region stiffness was higher with continuous-loop tape fixation compared with tied-suture fixation. There was also no significant difference in ultimate load between continuous-loop tape and tied-suture fixation. Therefore, continuous-loop tape fixation is biomechanically superior to tied-suture fixation and is thus a valid treatment option for all–soft tissue quadriceps tendon grafts in ACLR because it allows for improved graft fixation.

Previous studies regarding fixation of all–soft tissue quadriceps tendon grafts are limited in quantity, with a prior study evaluating various suture fixation techniques for all–soft tissue quadriceps tendon grafts.[16] The main finding was a significantly higher load to failure with a Krackow stitch configuration (553 ± 82 N) compared with baseball (366 ± 118 N) and whipstitch (392 ± 107 N) techniques ($P = .013$). Notably, there was no difference in the effect of stitch diameter on load to failure. Similarly, the Krackow stitch technique also demonstrated the lowest cyclic elongation (10.6 ± 2.6 mm), but the difference was not found to be significant. The mode of failure for the Krackow stitch technique was suture rupture, which occurred in 66% of specimens. In comparison with the present study, similar ultimate loads of 517.1 ± 149.2 N and 465.6 ± 64.6 N for the continuous-loop tape and tied-suture techniques, respectively, as well as the observed mode of failure were found. However, the cyclic elongation was notably less for continuous-loop tape (2.0 ± 0.4 mm) and tied suture (5.9 ± 1.3 mm), which is likely a result of the fewer number of cycles included in the cyclic testing protocol of the present study.

Prior work using tissue other than all–soft tissue quadriceps tendon grafts has demonstrated that continuous-loop tape fixation has greater ultimate load to failure and lower cyclic elongation than adjustable-loop fixation and interference screws.[1,4,12,31] The ultimate load and elongation of the quadriceps tendon with continuous-loop tape fixation seen in the current study are similar to those in prior studies looking at bone–patellar tendon–bone grafts.[35] Surgical fixation of the graft is key to preventing early failure, as the fixation method is the primary point of failure before graft incorporation.[14] This study shows that the mechanical benefits of continuous-loop tape fixation previously seen with other types of grafts are also present in all–soft tissue quadriceps tendon grafts. Notably, the addition of a locking stitch to prevent pullout of the continuous-loop device longitudinally along the fibers of the tendon graft is likely crucial to the result of this study.

The limitations of this study include the in vitro nature of the biomechanical testing, which did not include femoral or tibial tunnel placement. In vivo, tunnels are drilled to provide a close fit to the size of the graft, providing additional stability that is not seen in this ex vivo testing system. Additionally, multiple sizes and types of suture or methods of suturing (eg, whipstitch vs Krackow) were not compared, although a Krackow stitch was chosen as it has been demonstrated to prevent suture pullout.[16] There are multiple suture fixation options available for graft fixation; however, many authors have reported using No. 2 FiberWire or Ultrabraid, which have been demonstrated to have similar ultimate loads.[2,30,32,34] Finally, specimens up to age 92 years of age were used; however, this is unlikely to significantly affect the outcome of this study as prior literature has demonstrated that age alone does not affect in vivo tendon properties.[3] Additionally, specimens of similar ages were used in each group.

CONCLUSION

Continuous-loop tape fixation is superior to tied-suture fixation in regard to elongation and stiffness for all–soft tissue quadriceps tendon grafts, but there was no significant difference in ultimate load.

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