Tape-Reinforced Graft Suturing and Retensioning of Adjustable-Loop Cortical Buttons Improve Quadriceps Tendon Autograft Biomechanics in Anterior Cruciate Ligament Reconstruction: A Cadaveric Study

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Purpose: To investigate the biomechanical effects of tape-reinforced graft suturing and graft retensioning for all—soft tissue quadriceps tendon (ASTQT) anterior cruciate ligament reconstruction (ACLR) in a full-construct human cadaveric model. **Methods:** Harvested cadaveric ASTQT grafts were assigned to either (1) double-suspensory adjustable-loop cortical button device (ALD) fixation in which both graft ends were fixed with a suspensory fixation device with ($n = 5$) or without ($n = 5$) tape-reinforced suturing or (2) single-suspensory distal tendon fixation in which only the patellar end was fixed with an ALD ($n = 5$) or fixed-loop cortical button device (FLD) ($n = 5$). All specimens were prepared using a No. 2 whipstitch technique, and tape-reinforced specimens had an integrated braided tape implant. Graft preparation time was recorded for double-suspensory constructs. Samples were tested on an electromechanical testing machine using a previously published protocol simulating rehabilitative kinematics and loading. **Results:** Tape-reinforced graft suturing resulted in greater graft load retention after cycling (11.9% difference, $P = .021$), less total elongation (mean [95% confidence interval (CI)], 5.57 mm [3.50-7.65 mm] vs 32.14 mm [25.38-38.90 mm]; $P < .001$), greater ultimate failure stiffness (mean [95% CI], 171.9 N/mm [158.8-185.0 N/mm] vs 119.4 N/mm [108.7-130.0 N/mm]; $P < .001$), and less graft preparation time (36.4% difference, $P < .001$) when compared with unreinforced specimens. Retensioned ALD constructs had less cyclic elongation compared with FLD constructs (mean total elongation [95% CI], 7.04 mm [5.47-8.61 mm] vs 12.96 mm [8.67-17.26 mm]; $P = .004$). **Conclusions:** Tape-reinforced graft suturing improves time-zero ASTQT ACLR construct biomechanics in a cadaveric model with 83% less total elongation, 44% greater stiffness, and reduced preparation time compared with a whipstitched graft without tape reinforcement. ALD fixation improves construct mechanics when compared with FLD fixation as evidenced by 46% less total elongation. **Clinical Relevance:** Tape-reinforced implants and graft retensioning using ALDs improve time-zero ACLR graft construct biomechanics in a time-zero biomechanical model. Clinical studies will be necessary to determine whether these implants improve clinical outcomes including knee laxity and the incidence of graft rupture.

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The all—soft tissue quadriceps tendon (ASTQT) graft was initially described over 40 years ago by Marshall et al.[1] but has only recently gained widespread popularity for routine use in primary anterior cruciate ligament reconstruction (ACLR).[2] As the use of ASTQT grafts has increased, scientific investigation into these grafts has followed.[3] Histologic and biomechanical studies have shown increased collagen content within the ASTQT graft compared with other autograft options, a high load to failure, and a modulus of elasticity similar to the native anterior cruciate ligament (ACL).[4-6] Previous studies have suggested that the confluence of multiple tendinous components at differing trajectories and orientations results in a graft that functions at varying force vectors, distinguishing it from other commonly used ACL autografts.[7,8] Proponents of ASTQT grafts cite low donor-site morbidity, graft versatility, and favorable clinical outcomes compared with alternative autografts.[9,10]

Multiple strategies have been described and investigated for fixation of quadriceps tendon (QT) grafts for ACLR, including interference screw fixation, hybrid fixation using a cortical button and interference screw, and dual-suspensory fixation using cortical buttons.[11-17] All-inside ACLR, in which femoral and tibial sockets are drilled in an inside-out fashion, has gained widespread popularity over the past several years.[18] Advantages of all-inside ACLR include smaller incisions, bone preservation, the ability to tension and retension on both the femoral and tibial sides, and less postoperative pain.[2,9,10,19] ASTQT grafts are suitable for an all-inside ACLR technique because the harvesting technique allows surgeons to harvest the desired graft length without violating the rectus femoris, leaving normal tissue in situ.[20]

As ASTQT grafts have become more popular, specialized instrumentation and products have been developed to provide easy, reproducible, strong, and expedient QT graft preparation. Multiple studies have evaluated various graft suturing and fixation constructs for ASTQT grafts.[21-23] Moreover, recent publications have described techniques using an integrated braided tape implant for the fixation of ASTQT grafts.[24-26] Although the theoretical advantages of this type of implant include potentially faster graft preparation time and improved biomechanical strength, the biomechanical performance of this method of fixation has not been quantified. Additionally, in many biomechanical studies evaluating fixation and suture techniques for ASTQT grafts, only 1 end of the tendon was involved, rather than the entire graft construct.[21-23,27] Given the differences between the more heterogeneous multilaminar proximal tendon and the coalesced and more uniform distal tendon, the biomechanical properties of these different suture techniques may not be generalizable. From a clinical perspective, it is important to test the biomechanics of the entire construct to ensure that the "weakest link" of the graft is identified because this may influence early clinical outcomes. Although the clinical outcomes of ASTQT ACLR using contemporary techniques have been encouraging,[28] optimal methods of graft fixation remain to be defined and formed the impetus for this study in which an adjustable-loop implant with integrated braided tape was used for graft fixation in a full-construct model of ACLR.

The purpose of this study was to investigate the biomechanical effects of tape-reinforced graft suturing and graft retensioning for ASTQT ACLR in a full-construct human cadaveric model. We hypothesized that reinforcing graft suturing with braided tape would improve graft mechanics and reduce graft preparation time. We also hypothesized that adjustable-loop cortical button fixation with retensioning would improve construct mechanics compared with fixed-loop cortical button fixation.

Methods

Testing Design

Two suspensory configurations were used to evaluate ASTQT graft fixation techniques (Fig 1): (1) The double-suspensory (DS) configuration was performed with either a tape-reinforced whipstitch (DS-TR) or a conventional whipstitch (DS-W) on both ends of the ASTQT graft. All grafts included adjustable-loop cortical button devices (ALDs) for graft fixation. (2) The single-suspensory (SS) configuration was performed with a construct containing either an adjustable-loop cortical button device (SS-ALD) or a conventional fixed-loop cortical button device (SS-FLD) on the distal (patellar) end of the prepared ASTQT graft while the proximal tendon was clamped. No tape-reinforced whipstitch was used in either SS group. Each testing group comprised 5 specimens, for a total of 20 tested specimens, based on an a priori power analysis ($\alpha = .05$, $\beta = .20$) using data from the existing literature,[15,23] which revealed a minimum sample size of 4.

Graft Preparation

Twenty extensor mechanisms were harvested from 11 male and 3 female cadaveric donors (LifeNet Health, Virginia Beach, VA) with a mean age of 49.3 years (range, 28-68 years) and were randomly assigned to the aforementioned groups. Institutional review board approval from our institution was not required for cadaveric research. All tissue was sterilized with low-dose gamma irradiation (1.28-1.98 MRad) at ultra-low temperatures, previously shown to not alter allograft biomechanics in donors aged up to 65 years.[29]

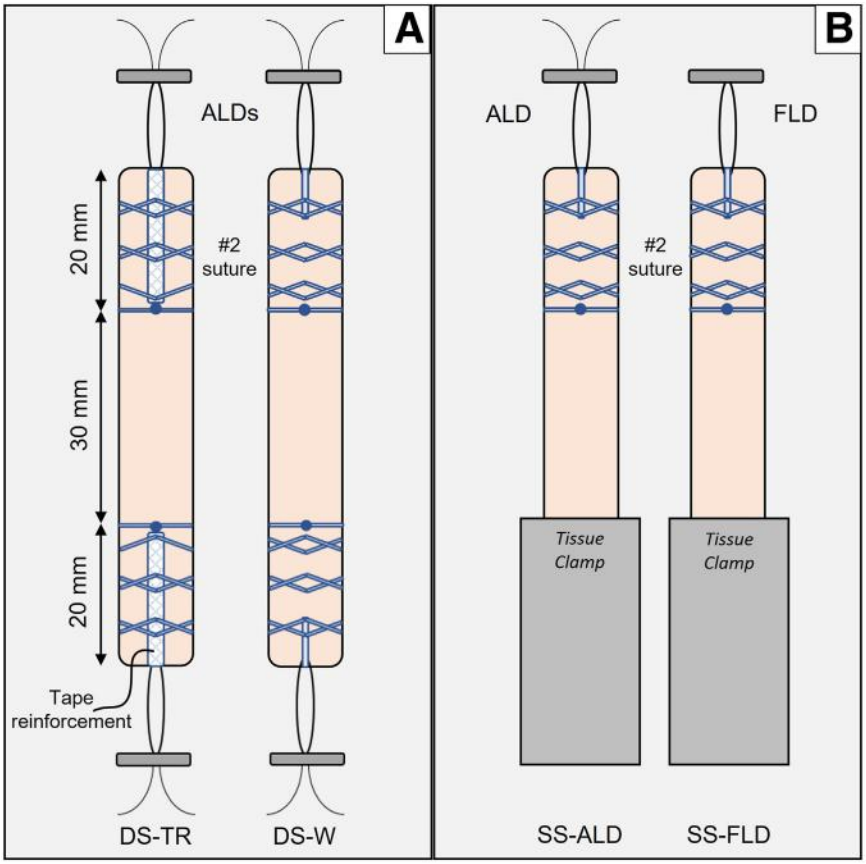

Fig 1. (A) Double-suspensory grafts underwent fixation using adjustable-loop devices (ALDs) with either tape-reinforced whipstitching (DS-TR) or unreinforced whipstitching (DS-W). (B) Single-suspensory grafts were prepared with either an adjustable-loop device (SS-ALD) or a fixed-loop device (SS-FLD) on the distal tendon. All suture passes had a pitch of 5 mm and were contained within 20 mm of the graft edge for cosmesis.

There were no signs of degenerative joint disease, prior knee injury, or other disease impacting tissue quality as assessed by the tissue vendor and a single board-certified sports medicine fellowship—trained orthopaedic surgeon (J.D.L.). Tissue was kept frozen at −20°C and thawed at room temperature for preparation and testing. ASTQT grafts were harvested from the central aspect of the tendon by the same surgeon and sized to 9 × 70 mm using a graft knife (Arthrex, Naples, FL).

DS constructs were prepared on both ends with ALDs (TightRope RT; Arthrex) by a single surgeon (J.D.L.). DS-TR grafts were prepared with an implant containing a preloaded ALD, No. 2 looped suture, and braided tape (FiberTag TightRope; Arthrex) per the SpeedWhip technique (Arthrex).[26] DS-W grafts were prepared with No. 2 looped suture (FiberLoop; Arthrex) using the SpeedWhip technique but without braided tape reinforcement; instead, a rip-stop was used in the final pass through tissue before the ALD was incorporated.[14] All consecutive suture passes had a pitch of 5 mm and were contained within 20 mm of each end of the graft with a 5-mm edge distance preserved. Graft preparation time by a single board-certified sports medicine fellowship—trained orthopaedic surgeon (J.D.L.) was recorded for each sample, starting at the first suture pass and ending immediately after knot tying.

SS constructs (SS-ALD and SS-FLD) were prepared with an identical whipstitch method to that described earlier and differed only in the incorporation of an ALD (TightRope RT; Arthrex) or fixed-loop cortical button device (FLD) (RetroButton; Arthrex). Graft preparation was performed by a single surgeon (J.D.L.) or 1 trained knee product design specialist for the techniques.

Reconstruction Technique

Acrylic blocks were used to model all-inside femoral and tibial tunnels as previously described to simulate the tunnels' radial forces while enabling direct visualization of the reconstruction.[15] Each 35-mm block consisted of a reamed 20-mm-long tunnel with varying diameter (9.5, 10, or 10.5 mm) and a 15-mm bone bridge (4.0 mm in diameter) to the cortex. The graft diameters of the proximal and distal ends were measured with graft-sizing tubes and assigned to acrylic blocks with similar tunnel diameters.

Before implantation, all prepared grafts were pretensioned on a graft preparation board (GraftPro; Arthrex) at 80 N for 5 minutes. The passing suture was used to flip the cortical button onto the acrylic cortex for both the femoral and tibial blocks. For DS grafts, the proximal end of the ASTQT graft was first fully shuttled into the tibial tunnel by alternatingly pulling on the shortening strands of the ALD and was then knotted with a standard surgeon's knot, followed by 4 alternating half-hitches and another surgeon's knot. Thereafter, the distal end of the ASTQT graft was shuttled into the femoral tunnel and the ALD was shortened until there was approximately 4 mm of space in the proximal end of the tunnel to allow for additional retensioning after pre-cycling (simulating intraoperative knee cycling) and before final knot tying. For SS grafts, the proximal end of the ASTQT was rigidly fixed using a soft-tissue clamp and only the femoral block was used per the technique described earlier.

Biomechanical Testing

Biomechanical testing was conducted on an electromechanical testing machine (ElectroPuls; Instron, Norwood, MA, USA) using a previously described protocol, with data continually sampled at 500 Hz.[15] The acrylic blocks and soft-tissue clamp were secured within vises affixed to the actuator and baseplate of the test frame such that the tunnel axes were in line with the applied load (Fig 2). The midbody (i.e., unsutured region) of all tested ASTQT grafts was 30 mm and represented the initial simulated ACL length at 30° of flexion in this study.

The testing sequence consisted of 10 position-controlled pre-cycles at 0.5 Hz simulating intraoperative knee cycling, manual retensioning for ALDs only, 1,000 position-controlled cycles at 0.75 Hz, 1,000 force-controlled cycles at 0.75 Hz, and a load-to-failure step at 50 mm/min (Fig 3). The singular manual retensioning was performed up to a maximum achievable load of 200 N as confirmed by the live force data from the electromechanical testing system. The 200-N load, replicated from the study by Karkosch et al.,[15] is a reasonably high retension load that generates a taut construct while still considering human factors. The position-controlled step used a weight-bearing knee flexion angle—ACL length relation wherein ACL length was observed to decrease by 1 mm and 3 mm at 30° and 90° of flexion, respectively, about the length at full extension.[30] The force-controlled step from 10 N to 250 N replicated in vivo weight-bearing ACL forces[31] and is similar in peak loading to that reported in other studies.[32,33]

Outcome Data

Initial load level, final load level, and graft load retention were determined from the position-controlled cycling. Initial elongation, dynamic elongation, total elongation, final hysteresis width, initial dynamic stiffness, and final dynamic stiffness were calculated from the force-controlled cycling. The valley (10-N) elongation values quantified plastic elongation (i.e., induced laxity) during different phases of cycling, whereas the hysteresis width represented the final elastic elongation behavior. Dynamic stiffness was defined as the linear slope generated between the valley (10-N) and peak (250-N) loads in a single cycle. Ultimate failure stiffness, ultimate failure load, and mode of failure were recorded. Ultimate failure stiffness was calculated as the linear slope within the range of 200 to 450 N. Graft preparation time was recorded as described earlier. The mode of failure was appraised by a biomechanical research engineer with 4 years of orthopaedic and sports medicine experience (B.L.S.).

Statistics

Statistical analysis including an a priori power analysis ($\alpha = .05$, $\beta = .20$) was performed using SigmaPlot (version 14.0; Systat, San Jose, CA, USA) and Minitab 19 (State College, PA, USA) software. The Student *t* test

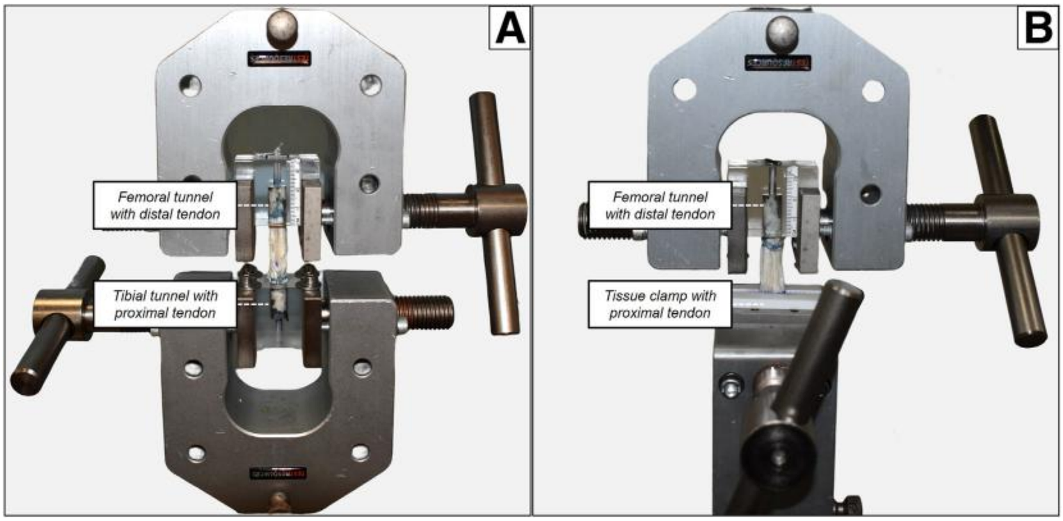

Fig 2. Experimental setups evaluating double-suspensory fixation (A) and single-suspensory fixation (B) on electromechanical testing system. Acrylic blocks modeled femoral and tibial tunnels for the quadriceps tendon graft.

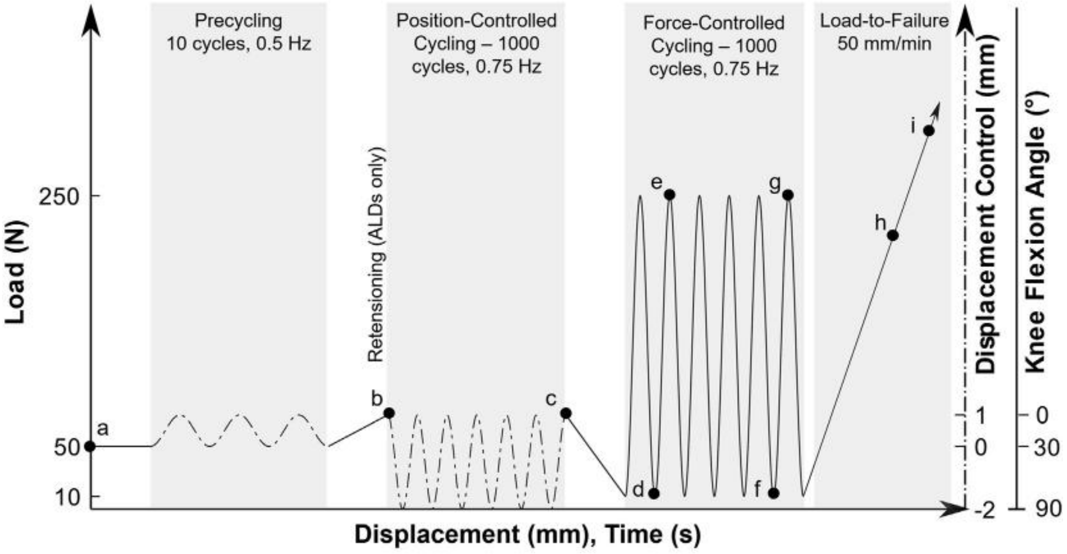

Fig 3. Testing protocol (adapted from Karkosch et al.[15]) for both models with data points (a-i) used to compute graft load retention (Δbc), initial elongation (Δad), dynamic elongation (Δdf), total elongation (Δaf), initial dynamic stiffness (Δde), final dynamic stiffness (Δfg), final hysteresis width (Δfg), and ultimate failure stiffness (Δhi). (ALD, adjustable-loop device.)

was used to compare parametric outcomes within the DS and SS configurations via the 1-tailed *P* value. The Welch *t* test was used for nonparametric data failing equal variance. Analysis-of-variance tests were used to analyze graft dimensions via the 2-tailed *P* value. Linear regression was used to determine whether a relation existed between number of grafts prepared and graft completion time.

Results

Final graft sizing between proximal and distal ASTQT graft ends (aggregate mean [95% confidence interval (CI)], 10.0 mm [9.7-10.2 mm]) for DS grafts was not significantly different within ($P = .851$) or between ($P = .575$) test groups. Final graft sizing between distal graft ends for SS grafts was not significantly different (aggregate mean [95% CI], 10.1 mm [9.9-10.3 mm]; $P = .347$). One sample in the DS-W group was excluded from analysis of these outcomes owing to loss of tension via suture pullout during retensioning. The biomechanical results of DS graft construct testing are shown in Table 1, and those of SS graft construct testing are presented in Table 2.

Position-Controlled Cycling

The DS-TR group had greater graft load retention than the DS-W group (mean [95% CI], 66.7%

Table 1. Biomechanical Results of DS Groups With Adjustable-Loop Fixation and No. 2 Whipstitching Alone or With Tape Reinforcement

Outcome	FiberTag TightRope (DS-TR)	No. 2 Whipstitch (DS-W)	*P* Value
Initial load level, N (b in Fig 3)	123.2 (100.3-146.2)	65.5 (52.9-78.2)	<.001[*,†]
Final load level, N (c in Fig 3)	82.1 (65.7-98.6)	38.7 (31.6-45.8)	<.001[†,‡]
Graft load retention, % (Δbc in Fig 3)	66.7 (60.9-72.6)	59.2 (52.5-65.9)	.021[†,‡]
Initial elongation, mm (Δad in Fig 3)	0.57 (0.19-0.95)	9.15 (2.13-16.17)	.014[*,†]
Dynamic elongation, mm (Δdf in Fig 3)	5.00 (3.26-6.74)	22.99 (15.69-30.30)	<.001[*,†]
Total elongation, mm (Δaf in Fig 3)	5.57 (3.50-7.65)	32.14 (25.38-38.90)	<.001[†,‡]
Final hysteresis width, mm (Δfg in Fig 3)	2.08 (1.87-2.28)	2.86 (2.67-3.04)	<.001[†,‡]
Initial dynamic stiffness, N/mm (Δde in Fig 3)	97.7 (84.3-111.2)	55.8 (46.3-65.2)	<.001[†,‡]
Final dynamic stiffness, N/mm (Δfg in Fig 3)	115.7 (103.5-127.9)	83.8 (78.5-89.1)	<.001[†,‡]
Ultimate failure stiffness, N/mm (Δhi in Fig 3)	171.9 (158.8-185.0)	119.4 (108.7-130.0)	<.001[†,‡]
Ultimate failure load, N	637.0 (516.9-757.0)	563.0 (533.1-592.8)	.068[‡]
Graft preparation time	7 min 36 s (7 min 6 s to 8 min 6 s)	10 min 59 s (10 min 37 s to 11 min 21 s)	<.001[†]

NOTE. Data are presented as mean (95% confidence interval). *P* values are 1-tailed with significance at $P < .05$.

DS, double-suspensory; TR, tape-reinforced whipstitching; W, unreinforced whipstitching.

[*] Nonparametric data for which Welch *t* test was used.

[†] Statistically significant ($P < .05$).

[‡] Parametric data for which Student *t* test was used.

Table 2. Biomechanical Results of SS Groups Using ALD or FLD

Outcome	Adjustable Loop (SS-ALD)	Fixed Loop (SS-FLD)	*P* Value
Initial load level, N (b in Fig 3)	102.5 (75.3-129.8)	67.5 (61.6-73.5)	.004*
Final load level, N (c in Fig 3)	67.4 (58.9-75.9)	39.0 (34.8-43.2)	<.001*
Graft load retention, % (Δbc in Fig 3)	67.4 (54.4-80.5)	57.9 (50.4-65.4)	.058
Initial elongation, mm (Δad in Fig 3)	0.89 (0.49-1.29)	2.85 (2.16-3.54)	<.001*
Dynamic elongation, mm (Δdf in Fig 3)	6.15 (4.88-7.43)	10.11 (6.17-14.06)	.015*
Total elongation, mm (Δaf in Fig 3)	7.04 (5.47-8.61)	12.96 (8.67-17.26)	.004*
Final hysteresis width, mm (Δfg in Fig 3)	1.89 (1.63-2.15)	1.90 (1.75-2.04)	.471
Initial dynamic stiffness, N/mm (Δde in Fig 3)	106.2 (91.7-120.8)	91.6 (84.0-99.1)	.019*
Final dynamic stiffness, N/mm (Δfg in Fig 3)	127.9 (110.7-145.2)	126.6 (117.4-135.8)	.426
Ultimate failure stiffness, N/mm (Δhi in Fig 3)	193.8 (176.7-211.0)	198.3 (190.3-206.3)	.266
Ultimate failure load, N	614.6 (531.0-698.1)	618.8 (517.4-720.3)	.465

NOTE. Data are presented as mean (95% confidence interval). *P* values are 1-tailed per the Student *t* test with significance at $P < .05$.
ALD, adjustable-loop device; FLD, fixed-loop device; SS, single-suspensory.
*Statistically significant ($P < .05$).

[60.9%-72.6%] vs 59.2% [52.5%-65.9%]; $P = .021$) (Table 1). The mean between-group percentage difference in graft load retention was 11.9%.

Force-Controlled Cycling

The DS-TR group had less initial elongation (mean [95% CI], 0.57 mm [0.19-0.95 mm] vs 9.15 mm [2.13-16.17 mm]; $P = .014$), dynamic elongation (mean [95% CI], 5.00 mm [3.26-6.74 mm] vs 22.99 mm [15.69-30.30 mm]; $P < .001$), and total elongation (mean [95% CI], 5.57 mm [3.50-7.65 mm] vs 32.14 mm [25.38-38.90 mm]; $P < .001$) than the DS-W group (Table 1, Fig 4). The DS-TR group also had greater initial dynamic stiffness (mean [95% CI], 97.7 N/mm [84.3-111.2 N/mm] vs 55.8 N/mm [46.3-65.2 N/mm]) and final dynamic stiffness (mean [95% CI], 115.7 N/mm [103.5-127.9 N/mm] vs 83.8 N/mm [78.5-89.1 N/mm]) ($P < .001$ for both). The SS-ALD group had less initial elongation (mean [95% CI], 0.89 mm [0.49-1.29 mm] vs 2.85 mm [2.16-3.54 mm]; $P < .001$), dynamic elongation (mean [95% CI], 6.15 mm [4.88-7.43 mm] vs 10.11 mm [6.17-14.06 mm]; $P = .015$), and total elongation (mean [95% CI], 7.04 mm [5.47-8.61 mm] vs 12.96 mm [8.67-17.26 mm]; $P = .004$) than the SS-FLD group.

Load to Failure

The DS-TR group had greater ultimate failure stiffness than the DS-W group (mean [95% CI], 171.9 N/mm [158.8-185.0 N/mm] vs 119.4 N/mm [108.7-130.0 N/mm]; $P < .001$). No differences in ultimate failure load were observed between groups. No differences in ultimate failure stiffness or load were identified between the SS-ALD and SS-FLD groups (Table 2). Figure 5 shows the ultimate failure stiffness in each group in relation to the native ACL stiffness range reported by Woo et al.[34]

In the DS configuration, the predominant failure mode was suture pullout at the proximal tendon, affecting 80% of DS-TR specimens (4 of 5) and 60% of DS-W specimens (3 of 5). All remaining failures consisted of suture rupture at the proximal end, except for 1 DS-TR rupture at the distal end. In the SS configuration, suture pullout failure affected 20% of both SS-ALD specimens (1 of 5) and SS-FLD specimens (1 of 5), with the remaining specimens undergoing suture rupture. No midsubstance graft failures were observed.

Graft Preparation Time

The DS-TR group had less graft preparation time than the DS-W group (7.60 minutes vs 10.98 minutes; mean percentage difference, 36.4%; $P < .001$). Linear regression showed no significant effect of the number of grafts prepared on the graft preparation time for the DS-TR ($P = .876$) and DS-W ($P = .611$) groups.

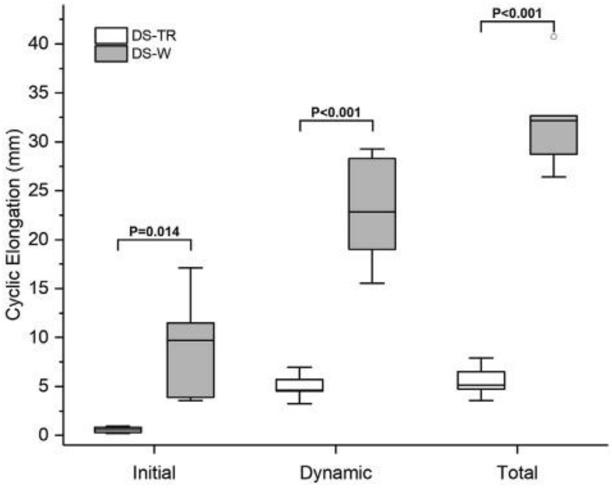

Fig 4. Initial, dynamic, and total elongation for double-suspensory groups with adjustable-loop fixation and tape-reinforced whipstitching (DS-TR) or unreinforced whipstitching (DS-W). The box signifies the interquartile range, the horizontal line signifies the median, and the whiskers signify the range. An open circle indicates a range value exceeding 1.5 times the interquartile range.

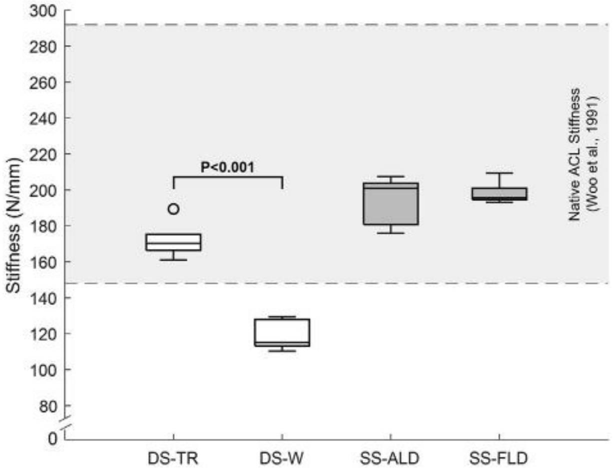

Fig 5. Ultimate failure stiffness for all test groups in reference to native tensile stiffness (220 ± 72 N/mm) of anterior cruciate ligament (ACL) reported by Woo et al.[34] The box signifies the interquartile range, the horizontal line signifies the median, and the whiskers signify the range. An open circle indicates a range value exceeding 1.5 times the interquartile range. (ALD, adjustable-loop device; DS, double-suspensory; FLD, fixed-loop device; SS, single-suspensory; TR, tape-reinforced whipstitching; W, unreinforced whipstitching.)

Discussion

The most important finding of this study was that the use of an adjustable-loop implant with integrated braided tape resulted in improved biomechanics compared with a commonly used whipstitch technique in a full-construct model of DS fixation for ASTQT ACLR. Specifically, total elongation was markedly reduced whereas graft fixation load, load retention, and stiffness were increased with the use of tape-reinforced implants. Additionally, graft preparation time was reduced when using tape-reinforced implants. With retensioning and knot tying, ALD constructs had significantly less cyclic elongation compared with FLD constructs. Thus, the hypotheses of the study are accepted. Specimens predominantly failed via suture pullout at the proximal multilaminar aspect of the QT, suggesting this to be the weak link of the construct and highlighting the importance of optimizing fixation on this side of the graft.

Historically, a challenge of the ASTQT has been adequate fixation of the graft, in part owing to its composition as a single-stranded tissue graft with a variable multilaminar musculotendinous proximal aspect.[1] Various techniques have been described that incorporate sutures through the ASTQT graft tissue into fixed- or adjustable-loop cortical buttons.[7,17,25,26] The suturing techniques investigated in our study were derived from those in previously published studies and those commonly used in the clinical setting. Techniques that rely on tying suture knots over a cortical button, as was performed in previous biomechanical studies by Kamada et al.[22] and Michel et al.,[23] are rarely used in the clinical setting today, especially on the femoral side. As such, for the comparison group in this study, we opted to use a whipstitch suturing technique using a looped suture that lacked tape reinforcement but instead used a rip-stop in the final throw before incorporating the ALD. This technique is commonly used in the clinical setting and requires fewer needle passes than a conventional whipstitch technique using a nonlooped suture; however, it was shown to result in higher displacement and tendon shredding compared with other graft suturing techniques, including 2 traditional Krackow techniques, in 1 study.[35]

During piloting for this study, a conventional No. 2 Krackow stitch was evaluated with both suture strands exiting the ASTQT tied to the ALD suture using a surgeon's knot, followed by 4 alternating half-hitches and a final surgeon's knot (similar to the method used in the study by Kamada et al.[22]). Each specimen treated with this technique failed before load-to-failure testing via suture unraveling, and as such, this group was aborted. Although this did not occur in the study by Kamada et al., the loading protocol in our study was much more aggressive and likely accounts for this observed difference between studies. During piloting, we also found that direct suturing of the ALD to the graft as described by Kamada et al. may not be amenable for use with the ALD because it can hinder the loop-shortening mechanism of the ALD. This technique may be more appropriate for FLDs.

An important finding of our study was the substantial difference in total elongation between the DS-TR and DS-W groups, with mean total elongation of 5.6 mm versus 32.1 mm. These results were not unexpected given that prior biomechanical studies using the ASTQT graft have also shown considerable elongation when using conventional graft suturing. In a study that used suspensory fixation on the proximal QT graft only, Michel et al.[23] found that doubled No. 2 Krackow suturing showed less elongation (mean, 10.6 mm) compared with whipstitching (mean, 18.7 mm) or baseball stitching (results not reported). In a similar study using suspensory fixation on the proximal aspect of a bovine QT graft, Kamada et al.[22] found less elongation when incorporating a continuous-loop device directly into the QT with simple No. 2 stitching (4.1 mm) compared with baseball stitching with knot tying to the continuous loop (8.2 mm) or direct baseball stitching to the cortical button (8.5 mm). Both Michel et al. and Kamada et al. used a uniaxial cyclic loading protocol with a peak load of 100 N for 500 cycles. Meanwhile, we used a DS configuration and a more aggressive testing protocol with a cyclic peak load of 250 N and 2,000 total cycles, which explains the increased elongation observed in the whipstitch group when compared with these previous studies and shows the favorable impact of tape reinforcement. In the SS configuration in this study, elongation values (7.04 mm for SS-ALD and 12.96 mm for SS-FLD) were consistent with data in these previous studies despite a more aggressive testing protocol. Together, these findings highlight the importance of a full-construct model in demonstrating the weakest link of the ACLR construct. Although the clinical implications of the markedly increased elongation observed in the DS-W group compared with the DS-TR group are unclear,[36] the use of a tape-reinforced implant for dual-suspensory ASTQT ACLR appears to improve time-zero biomechanical performance compared with conventional whipstitching.

As we anticipated, the proximal multilaminar aspect of the QT graft was shown to be the weakest link of the ACLR construct, given that nearly all failures occurred on that end of the graft. As shown in Figure 5, only the DS-W group fell outside of the previously described range for native ACL stiffness (mean ± standard deviation, 220 ± 72 N/mm),[34] suggesting that this graft preparation technique may be suboptimal. It is interesting to note that both SS groups in our study, which tested an identical whipstitch on the distal tendon only, showed findings within the previously described limits for native ACL stiffness. The inclusion of tape reinforcement appeared to help stabilize the proximal tendon and increase construct stiffness to native levels. Together, these findings suggest that the tape reinforcement technique used in our study may be of particular importance on the proximal aspect of the ASTQT tendon graft if suspensory fixation is used.

Tape-reinforced graft suturing improved dynamic biomechanical performance—but not ultimate failure load—in comparison to unreinforced specimens. The failure mode of suture pullout also had a similar frequency in both groups. These results suggest that the tape-reinforced implant reduces suture pullout primarily during physiological loading. Regardless, the ultimate failure load of all test groups surpassed the threshold of 454 N previously hypothesized as the load experienced by the ACL graft during most activities.[37] This threshold has not often been reached in prior studies of ASTQT suturing techniques. For instance, in the studies referenced earlier, Michel et al.[23] found that only the doubled Krackow suture group (553 N) met this criterion whereas none of the groups in the study by Kamada et al.[22] did so. Similarly, Arakgi et al.[21] found suboptimal failure loads for a stitching configuration incorporating a continuous-loop device into the QT graft (278 N). Although the ultimate load threshold has been defined, cyclic elongation is likely a more important parameter clinically than ultimate failure load, especially in terms of early postoperative rehabilitation during graft healing, incorporation, and ligamentization.[36] Graft fixation techniques that minimize cyclic elongation are preferable during this early postoperative period, and our findings suggest that tape-reinforced implants may provide better fixation at time zero.

As a secondary aim, the adjustable-loop implant tested in this study was compared with a fixed-loop implant to investigate how this difference impacted construct mechanics. Some concern still exists regarding loop lengthening for ALDs,[38-40] in part attributable to disputed methods and results of previous studies.[41] We found that with retensioning and knot tying, the ALD used in this study had a significantly greater final load level and less elongation compared with the FLD, which inherently cannot be retensioned. Our results are consistent with those of Noonan et al.,[42] who found that retensioning and knot tying eliminated the increased elongation of ALDs in a device-only model and decreased cyclic elongation by 50% in a cadaveric construct when compared with FLDs. We similarly found that the single retensioning and knot-tying step of the ALD used in this study reduced total cyclic elongation by 46% compared with the FLD. These results support the use of an ALD with retensioning and knot tying to optimize time-zero biomechanical performance when cortical button fixation is used for ASTQT graft fixation.

The tape-reinforced, adjustable-loop implant used in this study had reduced graft preparation time compared with its whipstitch control, which may translate into reduced operating room time. It is possible that having the adjustable-loop device incorporated into the braided tape—reinforced suture facilitated faster graft preparation time than having to incorporate a separate suture into an adjustable-loop device. Furthermore, this study provides quantitative support for use of the ALD technology, which can allow for shorter tunnel lengths, graft retensioning, and better seating of the graft in the tunnel compared with FLDs.[19] The improved biomechanics observed in the group receiving the tape-reinforced, adjustable-loop implant warrants further clinical investigation into the use of this device, given that these findings at time zero in a cadaveric model may not fully reflect the clinical setting and in vivo graft biomechanics.

Limitations

There are several limitations to this study. First, acrylic blocks were used to simulate bone tunnels, rather than human cadavers, and forces were pulled directly in line with the tissue, which does not simulate the shear or rotational forces experienced by the ACL or ACL graft in vivo. Moreover, this was a time-zero cadaveric biomechanical study that cannot simulate graft healing or dynamic muscle stabilization that may protect the graft during rehabilitation; therefore, it does not necessarily reflect in vivo biomechanics and ultimately clinical performance. Furthermore, the loading protocol in this study was relatively aggressive and likely exceeds what is experienced during the early rehabilitation process when little healing has occurred, resulting in graft elongation beyond what would typically be experienced in the early postoperative period. Graft preparation time was measured for 1 board-certified sports medicine fellowship–trained orthopaedic surgeon and could differ in the greater surgical population by experience level and training. For each specimen, full-thickness tendon harvesting was performed, which resulted in variable graft diameter[2] that may have impacted the results. Although most of the reported outcomes were significant and sufficiently powered, nonsignificant outcomes were underpowered owing to the relatively small sample sizes. Graft preparation time was only measured for the DS-TR and DS-W groups. The cadaveric donors were relatively older (mean age, 49.3 years) than most patients undergoing ACLR; as such, the quality of cadaveric tissue used may not have represented the population commonly undergoing ACLR. In addition, a single non-surgeon prepared 5 of the SS constructs, and this may have influenced the results of the SS constructs. Finally, although the surgeon who prepared the grafts had performed each graft preparation technique prior to the experiments, he has recently been using the DS-TR technique in the clinical setting, which may have impacted the timing results.

Conclusions

Tape-reinforced graft suturing improves time-zero ASTQT ACLR construct biomechanics in a cadaveric model with 83% less total elongation, 44% greater stiffness, and reduced preparation time compared with a whipstitched graft without tape reinforcement. ALD fixation improves construct mechanics when compared with FLD fixation as evidenced by 46% less total elongation.

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