Original Article

Whip-Lock Stitch Is Biomechanically Superior to Whipstitch for Semitendinosus Tendons

Miguel A. Diaz, M.S., Eric A. Branch, M.D., Jacob G. Dunn, D.O., Anthony Brothers, M.D., and Steve E. Jordan, M.D.

Purpose: To assess the biomechanical performance of different stitching methods using a suturing device by comparing the elongation, stiffness, failure load, and time to stitch completion in cadaveric semitendinosus tendons (STs) and quadriceps tendons (QTs). **Methods:** A total of 24 STs and 16 QTs were harvested from cadaveric knee specimens ($N = 40$). Samples were randomly divided into 2 groups: whipstitch (WS) and whip-lock (WL) stitch. Both tendon ends were clamped to a graft preparation stand, and a 2-part needle was used to place 5 stitches, each 0.5 cm apart. Stitching time was recorded. Samples were preconditioned and then underwent cyclic loading from 50 to 200 N at 1 Hz for 500 cycles, followed by load-to-failure testing at 20 mm/min. Stiffness (in newtons per millimeter), ultimate failure load (in newtons), peak-to-peak displacement (in millimeters), elongation (in millimeters), and failure displacement (in millimeters) were recorded. **Results:** Completion of the WS was significantly faster than the WL stitch in the ST ($P < .001$) and QT ($P = .004$). For the ST, the WL stitch exhibited higher ultimate failure loads and construct stiffness than the WS. Regarding the QT, the WL stitch showed higher stiffness and displacement than the WS; however, the ultimate failure load was higher for the WS in the QT. The ultimate failure load in the QT was higher than that in the ST for both stitches. In the ST, only 25% of WSs and 100% of WL stitches failed due to suture breakage. In the QT, suture breakage led to the failure of 100% of both the WL stitches and WSs. **Conclusions:** In the ST, the WL stitch resulted in improved biomechanical performance through higher ultimate load and fewer failures from tissue damage compared with the WS. In the QT, both the WS and the WL stitch showed similar biomechanical performance with ultimate failure loads above established clinical failure thresholds. **Clinical Relevance:** Various types of ligament and tendon injuries require suturing to enable repair or reconstruction. The success of ligament or tendon surgery often relies on soft-tissue quality. It is important to investigate the biomechanical properties of stitching techniques that help preserve soft-tissue quality as a step to determining their clinical suitability.

The success of ligament or tendon surgery often relies on soft-tissue fixation. Creating a stable soft-tissue suture construct may improve clinical outcomes by allowing early initiation of rehabilitation and providing stability during the healing phase.[1-3] Ultimately, the goals of soft-tissue suture repair or reconstruction include decreasing recovery time, restoring functionality, and achieving a successful return in terms of the patient's quality of life.[4] Various types of ligament and tendon injuries require suturing to enable repair or reconstruction, and the most common include tears of the anterior cruciate ligament (ACL), biceps tendon, and Achilles tendon.[5] In the United States, 33 million musculoskeletal injuries have been reported per year, 50% involving tendon and ligament injuries.[5,6]

Suturing techniques often require the use of a needle to repeatedly pass a suture through the tendon and are critical to the creation of a secure soft-tissue construct.[7] Clinically, the performance of a construct can be evaluated by surgeons based on its efficiency (time to prepare) and intraoperative preloading. For example, stitches that require multiple needle passes typically take more time and create more needle holes, increasing the risk of damage to the tissue.[8] In a

---

From the Foundation for Orthopaedic Research and Education, Tampa, Florida, U.S.A. (M.A.D.); Tallahassee Orthopedic Clinic, Panama City, Florida, U.S.A. (E.A.B.); St. Francis Orthopaedic Institute, Columbus, Georgia, U.S.A. (J.G.D.); and Andrews Research & Education Foundation, Gulf Breeze, Florida, U.S.A. (A.B., S.E.J.).

Research performed at Phillip Spiegel Orthopaedic Research Laboratory, Foundation for Orthopaedic Research and Education, Tampa, Florida, U.S.A.

Received July 31, 2023; accepted November 18, 2023.

Address correspondence to Steve E. Jordan, M.D., Andrews Research & Education Foundation, 1020 Gulf Breeze Pkwy, Gulf Breeze, FL 32561, U.S.A. E-mail: jordan.se@gmail.com

2666-061X/231023

https://doi.org/10.1016/j.asmr.2023.100853

benchtop setting, the performance of suture constructs can be described through biomechanical characteristics such as ultimate load, elongation, stiffness, and failure mode.

The 2 most prevalent stitching methods include the whipstitch (WS) and the Krackow stitch (KS).[3] Prior studies have tested the timing and biomechanics of the WS and KS techniques, but conclusions on which method is superior are divided, with some authors citing the speed benefits of the WS as the reason that this method is superior[7,9] but others citing that the strength benefits of the KS outweigh the additional time required.[4,10,11]

The WS was found to be time-efficient and to require the lowest number of needle holes[9]; however, the suture construct may damage the tissue by shredding or "cheese wiring" because forces are concentrated along the centerline of the tissue.[3,7] In contrast, the KS has long been a gold standard[12] for superior biomechanical performance because the locking mechanism added to the suture may help to transfer load from the tissue to the sutures.[10,11,13] However, it can be time-consuming and requires a large number of needle holes, which may also create stress risers and inevitably damage the tissue.[14,15]

The quality of the soft tissue may also influence the performance of a suture construct across all applications because lower-quality tissue sources are prone to tissue pull-through. For example, to reduce tissue pull-through for single-strand repairs such as in rotator cuff repair, several studies have evaluated different suture materials and load-sharing stitch techniques.[16-18] Another example can been seen in primary ACL reconstruction, in which the semitendinosus tendon (ST) often requires complex bundling techniques and/or harvesting of multiple tendon strands because of its small diameter and quality.[19] An alternative would be the use of different tissue types. The quadriceps tendon (QT) has been increasing in popularity as a graft choice for ACL reconstruction owing to advances in harvesting and preparation techniques, as well as potential advantages related to larger cross-sectional area as compared with the ST. Minimizing tissue pull-through is important clinically, especially when considering single-strand repairs, poorer-quality tissue, or smaller graft types. However, there are a limited number of biomechanical studies comparing stitching methods across different cadaveric tissue types.

We proposed and investigated a stitching method—the whip-lock (WL) stitch—that takes advantage of the locking suture mechanism of the KS while creating only a single needle hole. The WL stitch is enabled by a 2-part needle. The ST and QT were also selected as the subject of testing because they are the 2 most common soft-tissue autograft sources in ACL reconstruction.[20]

The purpose of this study was to assess the biomechanical performance of different stitching methods using a suturing device by comparing the elongation, stiffness, failure load, and time to stitch completion in cadaveric STs and QTs. We hypothesized that the QT would have significant biomechanical improvements when compared with the ST across the same stitch type.

Methods

All tissue dissection, harvesting, and biomechanical testing were performed at the Foundation for Orthopaedic Research and Education (Tampa, FL). All specimen instrumentation was completed at the Andrews Research & Education Foundation (Gulf Breeze, FL).

The suture device, EasyWhip (Winter Innovations, Knoxville, TN), is a 2-part needle that consists of an insert that slides in the back end of a needle tip. When the tip and insert portions are connected, a loop of suture is created. When they are separated, the suture is straight. The EasyWhip was used to create a traditional

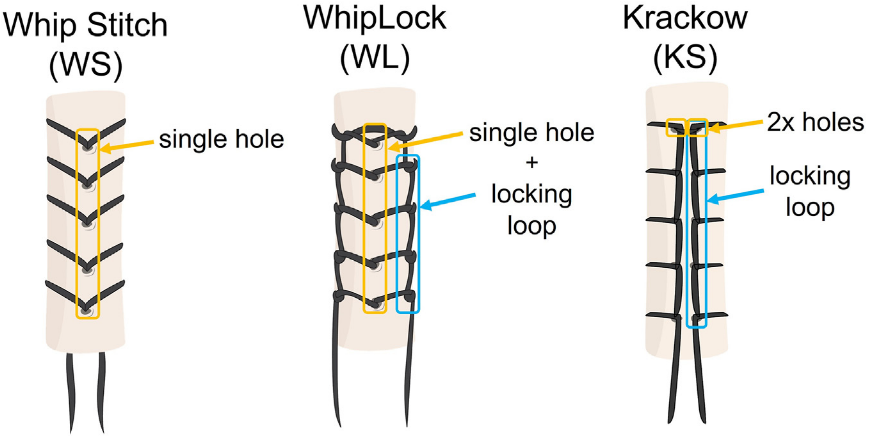

Fig 1. Comparison of Whipstitch (WS), whip-lock (WL) stitch, and the Krackow stitch (KS).

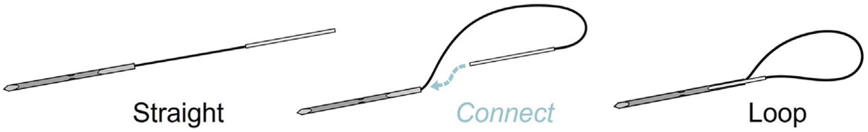

Fig 2. The 2-part needle begins with straight suture, and when the tip and insert portions are connected, a loop of suture is created.

WS and the WL stitch (a cross between a WS and a locking KS) (Fig 1).

Tendon Harvest and Specimen Preparation

A total of 32 cadaveric knee specimens were stored at −20°C and thawed at room temperature for 24 hours before dissection, instrumentation, and testing. For dissection, a total of 24 STs and 16 QTs were harvested (N = 40). In the ST group, the average age was 72.1 ± 11.2 years, and in the QT group, it was 72.5 ± 6.8 years. All tendons were cleaned and visually evaluated for the presence of tears or other abnormalities. The tendons were then randomly divided into the following 2 groups such that each user performed the WS and WL stitch. All samples were stitched with the same Easy-Whip suture needle (Fig 2). The length, width, and thickness of all tendons were measured with a digital caliper. In the ST group, the length was standardized to 10 cm, with average values of 10.8 ± 0.7 cm, 6.8 ± 1.4 mm, and 3.4 ± 0.8 mm for length, width, and thickness, respectively. The length of the QT was standardized to 7 cm, with average values of 7.0 ± 0.7 cm, 12.7 ± 4.2 mm, and 8.5 ± 1.7 mm for length, width, and thickness, respectively.

To perform the stitching, the cadaveric tendon samples were placed on a graft preparation stand and pretensioned. A skin marker was used to identify stitch placement along the center of the tendon. Five stitches were placed on 1 end approximately 0.5 cm apart (Fig 3). Two fellowship-trained surgeons performed all instrumentation (A.B. and S.E.J.). The time required to complete one 5-stitch series, as well as the entire stitching protocol, was recorded for each group.

Biomechanical Testing

Biomechanical evaluation was established using a previously published testing protocol.[4,7,9,10,15,21-23] Cyclical testing was performed using a servohydraulic testing machine (MTS Bionix; MTS Systems, Eden Prairie, MN) equipped with a 5-kN load cell. The tendon was coupled to the MTS actuator by passing it through a cryoclamp cooled by dry ice to a temperature of −5°C (monitored by temperature probe).

The 2 free ends of the suture were secured around the cylinder, which was rigidly fixed to the base of the MTS machine, with 6-throw square knots.[4,15] Length of suture loop, tendon grip length, and length of frozen tendon were standardized and measured across all specimens, where the cryoclamp was placed 1 cm above the first stitch, the total length of tendon exposed was 4 cm, and the length of suture to cylinder was 2 cm (Fig 4). Before testing, a visual check was performed, along with the use of a temperature probe, to verify that the tendon within the cryoclamp was frozen. All testing samples were then preconditioned to normalize viscoelastic effects and testing variability through application of cyclic loading to 25 to 100 N for 3 cycles. The samples were held at 50 N for 1 minute.[7] Thereafter, the samples were loaded to 50 to 200 N for 500 cycles at 1 Hz.[7] If samples survived cyclic loading, ramp-to-failure testing at 20 mm/min was performed. During cyclic loading, displacement data were collected from the actuator's linear variable differential transducer at cycles 1, 10, and 50, as well as every 100 cycles, as a measure of progressive construct elongation (in millimeters). During ramp-to-failure testing, stiffness (in newtons per millimeter), ultimate failure load (in

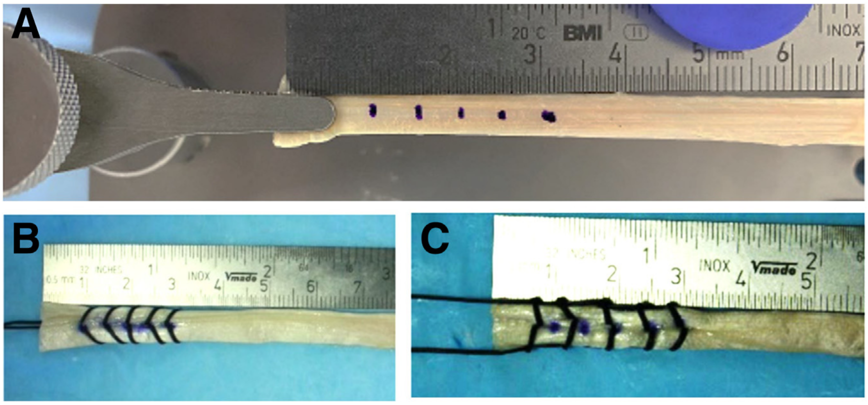

Fig 3. Example of tendon sample preparation using graft stand (A) to perform whipstitch (B) and whip-lock stitch (C).

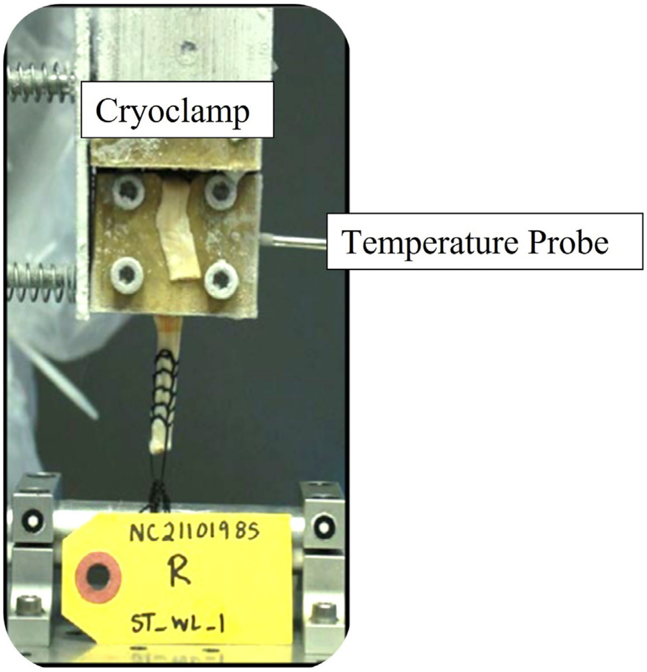

Fig 4. Biomechanical testing setup using cryoclamp to secure test sample.

newtons), ultimate failure displacement (in millimeters), and failure mode were recorded. Total elongation was defined as the difference in y-displacement between the first cyclic peak and the last cyclic peak, whereas peak-to-peak elongation was defined as the average of the maximum and minimum displacement across the last 3 cycles. Stiffness was defined as the linear portion (slope) of the load-displacement curve, and failure was defined as the first significant decrease in the monotonically increasing force profile. Specimens were visually monitored for any slipping within the clamp during testing, as well as on post-test analysis of the load-displacement curve, to ensure that slipping of the tendon within the clamp did not occur. Ultimate failure load was defined as the peak load at the onset of failure, and ultimate failure displacement was defined as the corresponding displacement at the point of failure. Failure mode was defined as tissue pull-through or suture breakage.

By use of mean and variance data from prior studies of similar scope,[4,7,15,21] a large effect size ($d = 1.4$) was used for an a priori power analysis. With a nonparametric design and a significance threshold of .05, the study was powered at the 0.83 level with a total sample size of 16 (8 samples per group) (G*Power, version 3.1.9.2; Heinrich-Heine-Universität Düsseldorf, Düsseldorf, Germany).

Statistical Analysis

The Wilcoxon rank sum test was performed to identify differences in biomechanical properties (peak-to-peak displacement, total elongation, stiffness, ultimate failure load, and failure displacement) within each tendon type across the 2 stitch constructs (WS and WL stitch). Moreover, the Kruskal-Wallis test was performed with post hoc analysis using the Steel-Dwass method to compare the biomechanical properties of each stitch construct between tendon types (ST and QT). Data are presented as mean ± standard deviation (SD). All statistical comparisons were performed with JMP software (JMP Pro 16 [2021]; SAS Institute, Cary, NC) at a significance level of $\alpha = .05$.

Results

Timing

Semitendinosus Tendon. In the ST, the total time to complete the entire 5-stitch series was significantly faster using the WS, 1 minute 31 seconds, when compared with the WL stitch, 2 minutes 48 seconds ($P = .00030$). No significant differences in total time to completion were found between the 2 users ($P = .066$).

Quadriceps Tendon. In the QT, the total time to complete the entire 5-stitch series was significantly faster using the WS, 1 minute 52 seconds, when compared with the WL stitch, 3 minutes 10 seconds ($P = .0039$). A significant difference in total time to completion was detected between the 2 users ($P = .041$).

ST Versus QT. When comparing the ST and QT, the total time to completion was similar, and no significant

Table 1. Data Summary for Stiffness, Load to Failure, Peak-to-Peak Displacement, Elongation, and Failure Displacement for ST

Study Group	n	Stiffness, N/mm	Ultimate Failure Load, N	Peak-to-Peak Displacement, mm	Elongation, mm	Failure Displacement, mm
Whipstitch	12	57.7 ± 13.87 (49.9-65.6)	240.7 ± 85.10 (192.5-288.8)	3.4 ± 2.46 (2.0- 4.8)	31.6 ± 14.82 (23.2-40.0)	53.0 ± 18.99 (42.3-63.7)
Whip-lock stitch	12	73.6 ± 5.05 (70.7-76.4)	339.0 ± 28.89 (322.7-355.4)	1.6 ± 0.25 (1.4-1.7)	31.3 ± 10.38 (25.4-37.1)	47.1 ± 11.74 (40.4-53.7)
P value		.003	.006	.064	.89	.26

NOTE. Data are presented as mean ± standard deviation (95% confidence interval).
ST, semitendinosus tendon.

Table 2. Data Summary for Stiffness, Load to Failure, Peak-to-Peak Displacement, Elongation, and Failure Displacement for QT

Study Group	n	Stiffness, N/mm	Ultimate Failure Load, N	Peak-to-Peak Displacement, mm	Elongation, mm	Failure Displacement, mm
Whipstitch	8	63.5 ± 8.4 (57.7-69.2)	378.9 ± 31.2 (357.3-400.5)	2.1 ± 0.2 (1.9-2.2)	35.6 ± 9.8 (28.9-42.4)	64.80 ± 12.90 (55.9-73.7)
Whip-lock stitch	8	75.2 ± 11.2 (67.4-82.9)	343.2 ± 22.3 (327.7-358.6)	2.1 ± 0.9 (1.5-2.7)	25.8 ± 9.5 (19.1-32.4)	45.70 ± 10.80 (38.2-53.2)
P value		.046	.031	.169	.104	.0045

NOTE. Data are presented as mean ± standard deviation (95% confidence interval).
QT, quadriceps tendon.

difference was observed using the WS ($P = .74$) or the WL stitch ($P = .81$). Overall, combining each stitch type, the time to complete the WS, on average, was 1 minute 39 seconds (SD, 31 seconds) whereas the time to complete the WL stitch, on average, was 2 minutes 57 seconds (SD, 52 seconds), with the WL stitch taking significantly longer ($P < .001$).

Biomechanical Properties

Semitendinosus Tendon. On comparisons between users in each stitch grouping for the ST, no significant differences were found across all biomechanical metrics of interest. Overall, it was observed that the WL stitch had significantly higher ultimate failure loads ($P = .0060$) and construct stiffness ($P = .0030$) when compared with the WS. Although peak-to-peak displacement was reduced using the WL stitch, this difference was not statistically significant ($P = .064$). Furthermore, no significant differences were found in total elongation and failure displacement (Table 1).

Quadriceps Tendon. On comparisons between users in each stitch grouping for the QT, a significant difference was found in construct stiffness ($P = .024$); however, no differences were found across the remaining biomechanical metrics of interest. Overall, it was observed that the WS had significantly higher ultimate failure loads ($P = .031$). The WL stitch had higher construct stiffness than the WS ($P = .046$). No significant differences were found in peak-to-peak displacement and total elongation. However, the WS had significantly more displacement at failure when compared with the WL stitch (Table 2).

ST Versus QT. On comparisons of the same stitch between the ST and QT, no differences were detected for peak-to-peak displacement (WS, $P = .99$; WL stitch, $P = .72$), total elongation (WS, $P = .85$; WL stitch, $P = .95$), or failure displacement (WS, $P = .77$; WL stitch, $P = .99$). Similarly, no significant difference was observed in construct stiffness for both the WS ($P = .89$) and WL stitch ($P = .91$).

The ultimate failure load was significantly higher in the QT than the ST when using the WS ($P = .031$). However, no difference in the ultimate failure load was detected between the 2 tendon types when using the WL stitch ($P = .99$) (Table 3).

The failure modes observed during testing were classified as tissue pull-through or suture breakage. In the WS specimens, the suture squeezed around the tendon, causing it to bulge as it was loaded; this was defined as tissue strangulation (Fig 5). The failure modes for the WS in the ST group consisted of tissue pull-through in 75% of samples and suture rupture in 25%; in contrast, for the WS in the QT group, all samples failed through suture rupture. However, when

Table 3. Data Summary for Stiffness, Load to Failure, Peak-to-Peak Displacement, Elongation, and Failure Displacement for ST Versus QT

Study Group	n	Stiffness, N/mm	Ultimate Failure Load, N	Peak-to-Peak Displacement, mm	Elongation, mm	Failure Displacement, mm
Whipstitch						
ST	12	57.7 ± 13.9 (49.9-65.6)	240.7 ± 85.1 (192.5-288.8)	3.4 ± 2.5 (2.0-4.8)	31.6 ± 14.8 (23.2-40.0)	53.0 ± 19.0 (42.3-63.7)
QT	8	63.5 ± 8.4 (57.7-69.2)	378.9 ± 31.2 (357.3-400.5)	2.1 ± 0.2 (1.9-2.2)	35.6 ± 9.8 (28.9-42.4)	64.8 ± 12.9 (55.9-73.7)
P value		.899	.0313	.998	.849	.769
Whip-lock stitch						
ST	12	73.6 ± 5.1 (70.7-76.4)	339.0 ± 28.9 (322.7-355.4)	1.6 ± 0.3 (1.4-1.7)	31.3 ± 10.4 (25.4-37.1)	47.1 ± 11.7 (40.4-53.7)
QT	8	75.2 ± 11.2 (67.4-82.9)	343.2 ± 22.3 (327.7-358.6)	2.1 ± 0.9 (1.5-2.7)	25.8 ± 9.5 (19.1-32.4)	45.7 ± 10.8 (38.2-53.2)
P value		.914	.998	.721	.949	.999

NOTE. Data are presented as mean ± standard deviation (95% confidence interval).
QT, quadriceps tendon; ST, semitendinosus tendon.

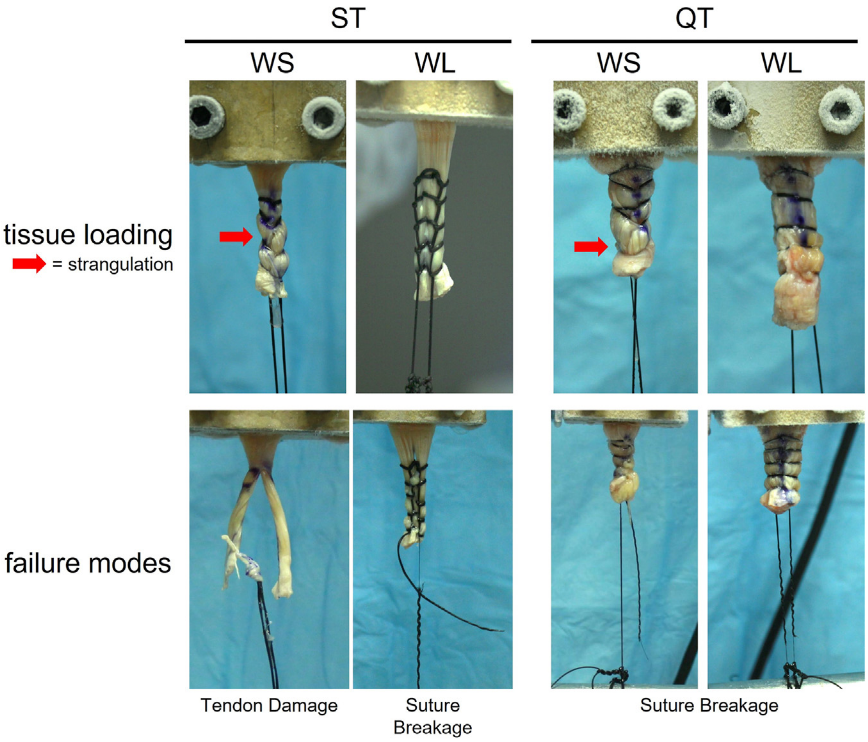

Fig 5. The failure modes experienced were tissue pull-through and suture breakage. Tissue strangulation (red arrow) was observed with the whipstitch (WS) method. (QT, quadriceps tendon; ST, semitendinosus tendon; WL, whip-lock stitch.)

the WL stitch was used, all samples failed owing to suture rupture in both the ST and QT groups (Table 4).

Discussion

The results of our study suggest that the WL stitch is the better option when presented with a smaller tendon such as the ST to minimize tissue pull-through and improve biomechanical performance. These outcomes partially supported our hypothesis that the QT would have significant biomechanical improvements when compared with the ST across the same stitch type. However, no significant differences were found for the WL stitch between the 2 tissue types, suggesting that the ST had equivalent biomechanical performance to that of the QT. Conversely, it was determined that the QT had significantly larger failure loads for the WS compared with the ST. Thus, when presented with tissue of unknown quality or size, the WL stitch provides consistent biomechanical performance. Moreover, it was determined that the choice of tendon type did not affect the time for the stitching methods tested. The completion of the WS took a similar amount of time for both the ST (1 minute 31 seconds) and QT (1 minute 52 seconds). Similarly, completing the WL stitch took a similar amount of time for the ST (2 minutes 48 seconds) and QT (3 minutes 10 seconds).

Creating a secure suture-tissue construct is critical for appropriate ligament or tendon repair and reconstruction.[7] Variables that may impact the security of the suture-tissue construct are often related to graft selection or fixation techniques, which have a wide variety of biomechanical characteristics.[4,24]

Camarda et al.[9] reported on the surgical time for graft preparation comparing the KS and WS using porcine flexor tendon. Their study included 5 independent examiners with different levels of medical training who performed 5 throws of each stitch configuration. On average, the KS took 69.1 seconds (range, 31.8-120 seconds) to complete and the WS took 59.9 seconds (range, 27-93 seconds) to complete. Direct comparison between studies is difficult because of varying factors such as the use of porcine tendon versus cadaveric tendon, type of tendon (flexor vs ST and QT) used, and type of suture used. However, for perspective, the times presented by Camarda et al. are similar to those for the WS in the ST group in our study.

Table 4. Failure Mode Classification

	Failure Mode, %	
Study Group	Tissue Pull-Through	Suture Breakage
Semitendinosus tendon		
Whipstitch configuration	75	25
Whip-lock stitch configuration	—	100
Quadriceps tendon		
Whipstitch configuration	—	100
Whip-lock stitch configuration	—	100

The ultimate load to failure has often been considered the most critical biomechanical factor when choosing a soft-tissue suture construct because it represents the ability of the construct to withstand potential loads that initially caused the injury.[24-28] Clinical failure thresholds vary based on specific anatomic site. For ACL reconstruction grafts, an ultimate failure load of 300 N is required because this represents the peak force exerted on the ACL during the first quarter of the gait cycle.[29-31] For a distal biceps repair, a clinical failure threshold of 220 N has been cited.[32,33] Typically, grafts are subjected to between 60 and 100 N of initial tension clinically.[7] Although all constructs that underwent testing achieved ultimate failure loads greater than 100 N, not all achieved failure loads above 300 N, which was set as the clinical failure threshold for this study.

In the ST, the WL stitch resulted in improved biomechanics through increased failure load by 41% and increased stiffness by 28% compared with the WS. The average failure load for the WS was less than 300 N, likely owing to the structure of the stitching methods. The WS may be more likely to fail at lower loads, as the suture is passed along the central axis of the tendon, increasing the chances of tissue pull-through, whereas the nature of the WL stitch allows the loads to be distributed throughout the suture construct. Although peak-to-peak displacement and failure displacement were reduced for the WL stitch, this was not found to be significant.

In the QT, the WL stitch had a slight decrease by 9% in failure load; however, there was an increase in stiffness of 18% and reduction in failure displacement by 29%. This is likely a result of suture failure owing to the difference in stiffness and displacement from load sharing across the WL stitch construct compared with the WS construct. Although there was a relative difference in load, the absolute value for both groups was above the 300-N clinical failure threshold.

Stiffness reflects the resistance to deformation of a structure; however, the clinical implications are unclear.[28] Our outcomes suggest that the WL stitch would be the better stitching method when using the ST or similar tendon that may be prone to tearing whereas either method can be used in the QT or similar tendon that tends to be thicker and less prone to tearing. It is interesting to note that the use of the WL stitch on an ST may provide equivalent biomechanical performance to a QT instrumented with either stitching method.

Elongation is another parameter that may have clinical value given that it has been shown to be a determinant of outcomes after Achilles tendon rupture.[3,34,35] It has also been associated with initial fixation to ensure tension is maintained until incorporation to native bone occurs.[13,36] The clinical threshold for failure has been cited in the literature as elongation greater than 3 mm.[36-38] However, this can be greatly influenced by the biomechanical test setup and loading protocol.[13] Unfortunately, there is currently no uniform recommendation of how much preload is required to replicate pre-tensioning of the graft when performed by the surgeon.[13] Despite the lack of standardization, reducing high values of elongation, specifically due to the cheese-wiring effect (tissue pull-through), is imperative because this type of tissue damage may lead to poor outcomes; thus, elongation above 3 mm was considered the clinical failure threshold in this study. We observed that the use of the WL stitch prevented failure due to tissue pull-through in both the ST and QT, suggesting a reliable stitch construct to minimize tissue damage and strangulation. This may be a characteristic of the WL stitching method that allows load sharing across the tendon as opposed to being localized. Moreover, the peak-to-peak displacement for these configurations remained below the 3-mm clinical threshold. Only the WS in the ST exhibited suture pullout and peak-to-peak displacement greater than 3 mm.

Michel et al.[13] evaluated the effects of various stitching methods (locking KS, baseball stitch, and WS) and suture diameters (No. 2 and No. 5 sizes) in cadaveric QT grafts. The samples were preloaded to 10 N and then cyclically loaded between 0 and 100 N for 500 cycles, followed by load-to-failure testing. Overall, the authors concluded that the double KS with No. 2 suture had the best biomechanical performance (high load to failure and low amount of elongation), for which the standard mode of failure was suture rupture. They observed that the WS and baseball stitch groups predominately failed owing to suture pullout. Although our study did not test the locking KS or baseball stitch, we observed a similar failure mechanism in the WS group, as all the tendon samples experienced pullout. Moreover, Michel et al. reported load-to-failure values of 392 ± 107 N (No. 2 suture) and 344 ± 78 N (No. 5 suture) for the WS group. For the QTs tested in our study, the load-to-failure value was similar in the WS group, at 378.9 ± 31.2 N. For the WL stitch group, the failure load was 343.2 ± 22.3 N.

Similarly, Hahn et al.[10] examined the KS and WS in porcine flexor tendons with a varying number of suture throws. The loading protocol used called for a preload of 5 N for 1 minute, followed by cyclic loading from 20 to 200 N at 1 Hz for 200 cycles. The ultimate strength for the KS with 4 throws was 319.4 ± 21.7 N, and that for the WS was 332.8 ± 26.2 N. In contrast to our findings, the failure mode was suture breakage in all cases, which is likely because of the suture material and may explain lower failure loads. The loading protocol appears to be on the lower cyclic range, whereas our protocol is more comparable to that of Sakaguchi et al.,[11] as we subjected the tendons to more rigorous loads. Several studies have shown the influence of different techniques on maximum load to failure and elongation.[39-41]

The WL stitching method introduced in this investigation has shown to provide adequate performance in both the ST and QT. Future studies will evaluate the performance of the WL stitch compared with the KS, as well as other suture materials; its performance in other soft-tissue models such as the Achilles or biceps tendon; and the use of suspensory buttons.

Limitations

This study is not without its limitations. One limitation was the lack of direct comparison between the gold-standard KS and the WS and WL stitching methods. The inclusion of the KS could have helped strengthen our findings. This investigation presents data on the biomechanical properties of each tendon at time zero and cannot take into account tissue healing. The use of human cadaveric tissue introduces many variables related to quality owing to age. No differences were found between study groups in age or tendon measurements. A limitation in soft-tissue suture application is the issue of suture creep, which can be related to suture material and tensioning.[17,42,43] Although pretensioning was performed to minimize viscoelastic creep before cyclical testing, the loading was in a single direction and does not replicate in vivo loading conditions.[4,7] Moreover, knot slippage may be a concern depending on the technique used for the fixation construct.[13] We did not observe knot slippage throughout testing.

Another limitation was the inclusion of only 2 surgeons, which makes it difficult to discern the impact of our conclusions regarding stitch time. More participants would be required to establish a strong basis of how much faster the WS and WL stitch can be performed and how this may impact operating costs. Between the 2 surgeon users performing the stitches, there was a significant difference in total time to stitch completion in the QT; however, this was noted to be due to the tissue slipping within the preparation stands. This may have also contributed to the difference in construct stiffness, where the final suture tension applied by 1 surgeon may have been slightly less to prevent tendon slipping from the preparation stand. However, no difference in biomechanical performance was found between the 2 users, suggesting that the quality of stitching was not compromised. The testing was performed in a non-aqueous environment, but care was taken to continuously hydrate tissue with 0.9% saline solution.

Finally, the biomechanical model has been simplified to focus on the suture-tendon interface and therefore does not reflect how constructs would commonly be used in ACL reconstruction. Specifically, STs are commonly folded or bundled in multiple strands. Although the testing model does not replicate the behavior experienced in the human knee joint that may contribute to the performance and stability of the graft, it can be considered the worst-case scenario. Previous studies have shown higher loads to failure with physiological stresses compared with a straight line of pull.[26,44] The loading protocol selected to test the samples is similar to published protocols.[10,11,13,42]

Conclusions

In the ST, the WL stitch resulted in improved biomechanical performance through higher ultimate load and fewer failures from tissue damage compared with the WS. In the QT, both the WS and the WL stitch showed similar biomechanical performance with ultimate failure loads above established clinical failure thresholds.

Disclosures

The authors report the following potential conflicts of interest or sources of funding: This study was funded by Winter Innovations and was supported by the National Science Foundation (under grant No. 2112103). M.A.D. receives a research grant from Winter Innovations (grant No. 2112103, paid directly to the Foundation for Orthopaedic Research and Education). In addition, the Foundation for Orthopaedic Research and Education has received a research grant from DePuy Mitek. A.B. receives support from Sanara MedTech and ZIMVIE, outside the submitted work. S.E.J. receives support from Arthrex, CGG Medical, Vericel, GE Healthcare, BREG, and SI-BONE, outside the submitted work. All other authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article. Full ICMJE author disclosure forms are available for this article online, as supplementary material.

References

1. Kearney RS, Costa ML. Current concepts in the rehabilitation of an acute rupture of the tendo Achillis. *J Bone Joint Surg Br* 2012;94:28-31.
2. Maffulli N, Tallon C, Wong J, Lim KP, Bleakney R. Early weightbearing and ankle mobilization after open repair of acute midsubstance tears of the Achilles tendon. *Am J Sports Med* 2003;31:692-700.
3. Muscatelli S, Walley KC, Daly-Seiler CS, et al. Biomechanical comparison of a novel multiplanar, perpendicular whipstitch with the Krackow stitch and standard commercial whipstitch. *Orthop J Sports Med* 2022;10: 23259671221107034.
4. Ostrander RV III, Saper MG, Juelson TJ. A biomechanical comparison of modified Krackow and locking loop suture patterns for soft-tissue graft fixation. *Arthroscopy* 2016;32: 1384-1388.

5. Wu F, Nerlich M, Docheva D. Tendon injuries: Basic science and new repair proposals. *EFORT Open Rev* 2017;2: 332-342.
6. James R, Kesturu G, Balian G, Chhabra AB. Tendon: Biology, biomechanics, repair, growth factors, and evolving treatment options. *J Hand Surg Am* 2008;33: 102-112.
7. Barber FA, Howard MS, Piccirillo J, Spenciner DB. A biomechanical comparison of six suture configurations for soft tissue-based graft traction and fixation. *Arthroscopy* 2019;35:1163-1169.
8. Hong CK, Lin CL, Kuan FC, Wang PH, Yeh ML, Su WR. Longer stitch interval in the Krackow stitch for tendon graft fixation leads to poorer biomechanical property. *J Orthop Surg (Hong Kong)* 2018;26: 2309499018799514.
9. Camarda L, Giambartino S, Lauria M, Saporito M, Triolo V, D'Arienzo M. Surgical time for graft preparation using different suture techniques. *Muscles Ligaments Tendons J* 2016;6:236-240.
10. Hahn JM, Inceoglu S, Wongworawat MD. Biomechanical comparison of Krackow locking stitch versus nonlocking loop stitch with varying number of throws. *Am J Sports Med* 2014;42:3003-3008.
11. Sakaguchi K, Tachibana Y, Oda H. Biomechanical properties of porcine flexor tendon fixation with varying throws and stitch methods. *Am J Sports Med* 2012;40: 1641-1645.
12. Krackow KA. The Krackow suture: How, when, and why. *Orthopedics* 2008;31:931-933.
13. Michel PA, Domnick C, Raschke MJ, et al. Soft tissue fixation strategies of human quadriceps tendon grafts: A biomechanical study. *Arthroscopy* 2019;35:3069-3076.
14. Wang RY, Arciero RA, Obopilwe E, Mazzocca AD. A comparison of structural and mechanical properties of tubularized and native semitendinosus graft. *Am J Sports Med* 2010;38:1246-1249.
15. White KL, Camire LM, Parks BG, Corey WS, Hinton RY. Krackow locking stitch versus locking premanufactured loop stitch for soft-tissue fixation: A biomechanical study. *Arthroscopy* 2010;26:1662-1666.
16. Burkhart SS, Denard PJ, Konicek J, Hanypsiak BT. Biomechanical validation of load-sharing rip-stop fixation for the repair of tissue-deficient rotator cuff tears. *Am J Sports Med* 2014;42:457-462.
17. Neeley RA, Diaz MA, Gorman RA II, Frankle MA, Mighell MA. A weaving rip-stop technique leads to a significantly increased load to failure and reduction in suture-tendon cut-through in a biomechanical model of rotator cuff repair. *Arthrosc Sports Med Rehabil* 2021;3: e1263-e1272.
18. Owens BD, Algeri J, Liang V, DeFroda S. Rotator cuff tendon tissue cut-through comparison between 2 high-tensile strength sutures. *J Shoulder Elbow Surg* 2019;28: 1897-1902.
19. Brown CH Jr. Editorial commentary: How to increase hamstring tendon graft size for anterior cruciate ligament reconstruction. *Arthroscopy* 2018;34:2641-2646.
20. Buerba RA, Boden SA, Lesniak B. Graft selection in contemporary anterior cruciate ligament reconstruction. *J Am Acad Orthop Surg Glob Res Rev* 2021;5:e21.00230.
21. Deramo DM, White KL, Parks BG, Hinton RY. Krackow locking stitch versus nonlocking premanufactured loop stitch for soft-tissue fixation: A biomechanical study. *Arthroscopy* 2008;24:599-603.
22. Ettinger M, Dratzidis A, Hurschler C, et al. Biomechanical properties of suture anchor repair compared with transosseous sutures in patellar tendon ruptures: A cadaveric study. *Am J Sports Med* 2013;41:2540-2544.
23. Howard ME, Cawley PW, Losse GM, Johnston RB III. Bone-patellar tendon-bone grafts for anterior cruciate ligament reconstruction: The effects of graft pretensioning. *Arthroscopy* 1996;12:287-292.
24. Urchek R, Karas S. Biomechanical comparison of quadriceps and 6-strand hamstring tendon grafts in anterior cruciate ligament reconstruction. *Orthop J Sports Med* 2019;7:2325967119879113.
25. Butler DL, Juncosa N, Dressler MR. Functional efficacy of tendon repair processes. *Annu Rev Biomed Eng* 2004;6: 303-329.
26. Noyes FR, Butler DL, Grood ES, Zernicke RF, Hefzy MS. Biomechanical analysis of human ligament grafts used in knee-ligament repairs and reconstructions. *J Bone Joint Surg Am* 1984;66:344-352.
27. Sasaki N, Farraro KF, Kim KE, Woo SL. Biomechanical evaluation of the quadriceps tendon autograft for anterior cruciate ligament reconstruction: A cadaveric study. *Am J Sports Med* 2014;42:723-730.
28. Shani RH, Umpierez E, Nasert M, Hiza EA, Xerogeanes J. Biomechanical comparison of quadriceps and patellar tendon grafts in anterior cruciate ligament reconstruction. *Arthroscopy* 2016;32:71-75.
29. Cheruvu B, Neidhard-Doll A, Goswami T. Gender-specific anterior cruciate ligament—Gait forces. *Adv Gen Pract Med* 2022;4:42-47.
30. Marieswaran M, Jain I, Garg B, Sharma V, Kalyanasundaram D. A review on biomechanics of anterior cruciate ligament and materials for reconstruction. *Appl Bionics Biomech* 2018;2018:4657824.
31. Shelburne KB, Pandy MG, Anderson FC, Torry MR. Pattern of anterior cruciate ligament force in normal walking. *J Biomech* 2004;37:797-805.
32. Idler CS, Montgomery WH III, Lindsey DP, Badua PA, Wynne GF, Yerby SA. Distal biceps tendon repair: A biomechanical comparison of intact tendon and 2 repair techniques. *Am J Sports Med* 2006;34:968-974.
33. Shukla DR, Morrey BF, Thoreson AR, An KN, O'Driscoll SW. Distal biceps tendon rupture: An in vitro study. *Clin Biomech (Bristol, Avon)* 2012;27:263-267.
34. Kangas J, Pajala A, Ohtonen P, Leppilahti J. Achilles tendon elongation after rupture repair: A randomized comparison of 2 postoperative regimens. *Am J Sports Med* 2007;35:59-64.
35. Maquirriain J. Achilles tendon rupture: Avoiding tendon lengthening during surgical repair and rehabilitation. *Yale J Biol Med* 2011;84:289-300.
36. Barrow AE, Pilia M, Guda T, Kadrmas WR, Burns TC. Femoral suspension devices for anterior cruciate ligament reconstruction: Do adjustable loops lengthen? *Am J Sports Med* 2014;42:343-349.
37. Daniel DM, Stone ML, Sachs R, Malcom L. Instrumented measurement of anterior knee laxity in patients with

acute anterior cruciate ligament disruption. *Am J Sports Med* 1985;13:401-407.

38. Eguchi A, Ochi M, Adachi N, Deie M, Nakamae A, Usman MA. Mechanical properties of suspensory fixation devices for anterior cruciate ligament reconstruction: Comparison of the fixed-length loop device versus the adjustable-length loop device. *Knee* 2014;21:743-748.
39. Dahl KA, Patton DJ, Dai Q, Wongworawat MD. Biomechanical characteristics of 9 arthroscopic knots. *Arthroscopy* 2010;26:813-818.
40. Lo IK, Burkhart SS, Chan KC, Athanasiou K. Arthroscopic knots: Determining the optimal balance of loop security and knot security. *Arthroscopy* 2004;20:489-502.
41. Rodes SA, Favorito PJ, Piccirillo JM, Spivey JT. Performance comparison of a pretied suture knot with three conventional arthroscopic knots. *Arthroscopy* 2015;31: 2183-2190.
42. Arakgi ME, Burkhart TA, Hoshino T, Degen R, Getgood A. Biomechanical comparison of three suspensory techniques for all soft tissue central quadriceps tendon graft fixation. *Arthrosc Sports Med Rehabil* 2022;4:e843-e851.
43. Morrison L, Haldane C, de Sa D, Findakli F, Simunovic N, Ayeni OR. Device-assisted tensioning is associated with lower rates of graft failure when compared to manual tensioning in ACL reconstruction. *Knee Surg Sports Traumatol Arthrosc* 2018;26:3690-3698.
44. Woo SL, Hollis JM, Adams DJ, Lyon RM, Takai S. Tensile properties of the human femur-anterior cruciate ligament-tibia complex. The effects of specimen age and orientation. *Am J Sports Med* 1991;19:217-225.