

Comparison of Biomechanical Failure Loads Between Tape-Type and Conventional Sutures in Internal Knotless Anchor-Based Constructs

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Background: Despite the increasing prevalence of tape-type sutures, whether internal knotless anchors can consistently affix tape-type sutures has not been thoroughly investigated.

Purpose: To evaluate whether substituting tape-type sutures for conventional sutures influences the suture-holding strength of internal knotless anchors.

Study Design: Controlled laboratory study. Level of evidence, 5.

Methods: A total of 3 internal knotless anchors were tested: a spiral core clamping anchor (Footprint Ultra PK), a winged clamping anchor (PopLok), and a spooling anchor (ReelX STT). Four constructs were compared for each type of anchor, with the anchor double or quadruple loaded with tape-type sutures or conventional sutures. The testing protocol comprised preloading suture tension to 10 N; cyclic loading, in which tension increased in increments of 10 N from 10 to 90 N; and a load-to-failure stage set at a speed of 0.5 mm/s. The clinical failure load (CFL) was defined as suture slippage of ≥ 3 mm. Also, 1-way analysis of variance and power analysis were used to compare the CFLs of the constructs.

Results: For the quadruple-loaded spiral core clamping anchors, a significant reduction in CFLs was seen with conventional sutures over tape-type sutures (138.10 ± 4.73 vs 80.00 ± 12.25 N, respectively; $P < .001$). This reduction was not observed under the double-loaded condition (conventional vs tape type: 76.00 ± 5.48 vs 80.00 ± 10.00 N, respectively). Substitution of the suture materials did not significantly reduce the CFLs for the winged clamping anchors (conventional vs tape type: 40.00 ± 10.00 vs 30.00 ± 7.07 N for double loaded, respectively, and 64.00 ± 13.41 vs 50.00 ± 10.00 N for quadruple loaded, respectively) or the spooling anchors (conventional vs tape type: 62.00 ± 19.23 vs 56.32 ± 20.20 N for double loaded, respectively, and 72.00 ± 21.68 vs 84.00 ± 13.42 N for quadruple loaded, respectively).

Conclusion: Substituting tape-type sutures for conventional sutures increased the CFLs of some internal knotless anchors. With specific suture-anchor combinations, quadruple-loaded conventional suture anchors had CFLs higher than those of double-loaded conventional suture anchors.

Clinical Relevance: When multiple tape-type sutures are used in conjunction with a clamping anchor, clinicians should note a possible reduction in CFLs and resultant early suture slippage.

Keywords: knotless anchor; tape-type sutures; sutures; failure load

Knotless suture anchors have been gaining popularity, thanks to their easier application, cost-effectiveness, and reduction of knot-driven secondary complaints while providing clinical and biomechanical outcomes similar to those

of their knotted counterparts.^{4,6,17,18,20,23,30,34} External knotless anchors rely on an interference suture locking mechanism between the anchor surface and bone,^{27,37} while internal knotless anchors hold suture materials between the anchor body and a core metallic rod.³⁵ Because internal knotless anchors use clamping mechanisms, however, several concerns exist. Wieser et al³⁵ found that the suture-holding strength could not reach half of the anchor

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pull-out strength; that is, the load at which the sutures slipped was less than half of the load at which the anchors were pulled out of the bone. Early suture slippage with knotless anchors has been reported to cause gap formation between the repaired tendon and the bone,^{21,39} and delayed suture slippage leads to adjacent bursitis.¹³

Tape-type sutures have also become increasingly popular in recent years.² Benefits of tape-type sutures include decreased irritation in the subacromial space, better stress distribution over degenerative tissue, and improved biomechanical arthroscopic sliding knot properties.^{15,29} Rotator cuff repair sites using tape-type sutures have higher contact pressure, higher loads to failure, and a smaller gap formation compared with those using conventional sutures.^{2,16,24} Similar conclusions have been drawn from biomechanical studies on quadriceps, patellar, and Achilles tendon repair procedures using tape-type sutures.^{12,25,26,32} Deranlot et al⁷ compared the abrasive effects of conventional sutures and tape-type sutures and concluded that the variance in coating materials and shape resulted in distinct frictional properties. Despite the increasing prevalence of tape-type sutures, whether internal knotless anchors can consistently affix tape-type sutures has not been thoroughly investigated.

The current study investigated whether substituting tape-type sutures for conventional sutures influences the suture-holding strength of internal knotless anchors. A total of 3 types of internal knotless anchors were tested. We hypothesized that under typical conditions of double or quadruple loading, this type of replacement would not reduce the failure loads of internal knotless anchors.

METHODS

Experimental Procedure

A total of 60 synthetic bone blocks (60 × 40 × 40 mm) were purchased from Sawbones (Pacific Research Laboratories). The bone blocks comprised solid, rigid polyurethane foam blocks (density, 0.16 g/cm³) with a 2-mm layer of short fiber-filled epoxy (density, 1.63 g/cm³) on top, simulating human cancellous and cortical bone, respectively.¹⁴ Similar bone blocks have been used in previous biomechanical studies to simulate the human greater tuberosity, the density of which ranged from 0.10 ± 0.03 to 0.18 ± 0.04 g/cm³.³⁷

Overall, 3 types of knotless suture anchors with diameters of 4.5 mm were examined in the present study, for which the fixation mechanism was internal. They are shown in Figure 1 and described as follows:

1. Spiral core clamping anchor: The Footprint Ultra PK (Smith & Nephew). This anchor clamps suture materials between an internal anchor plug and the anchor body. Barbs on the anchor body prevent pullout from cancellous bone.
2. Winged clamping anchor: The PopLok (Conmed Linvatec). This anchor clamps the suture materials between the outer and inner shaft. The 2 wings popping out from the anchor body after deployment provide subcortical fixation against pullout.
3. Spooling anchor: The ReelX STT (Stryker). An anchor body expands progressively when the anchor is being deployed. It uses a spooling mechanism for internal fixation in which the sutures are incrementally tensioned and advanced for every 60° revolution of the knob.

A 4.0-mm unicortical drill hole was predrilled in the middle of a foam block. Each internal knotless anchor was loaded with either No. 2 Hi-Fi suture (Conmed Linvatec) or SutureTape (Arthrex). Either 2 or 4 sutures were loaded (double-loaded group and quadruple-loaded group) onto each combination because these amounts are typically used in tendon repair procedures. To summarize, a total of 12 constructs were tested (3 types of anchors, 2 kinds of materials, and 2 amounts of sutures). A loaded suture anchor was tapped in and deployed according to the manufacturer's instructions. The construct was firmly fastened onto the base of a material testing system (AG-X; Shimadzu) fitted with a 1-kN load cell (Figure 2).

Biomechanical Testing Setup

Double-Loaded Anchors. To load equally onto each suture limb, the 2 suture limbs were tied into a loop across a metallic ring connected to the load cell. Each suture limb was marked with a distinctive color so that the extent of suture slippage could be quantified (Figure 2C).

Quadruple-Loaded Anchors. To load equally onto the 4 suture limbs, the limbs were tied into 2 loops. The 2 loops

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Ethical approval was not sought for the present study.

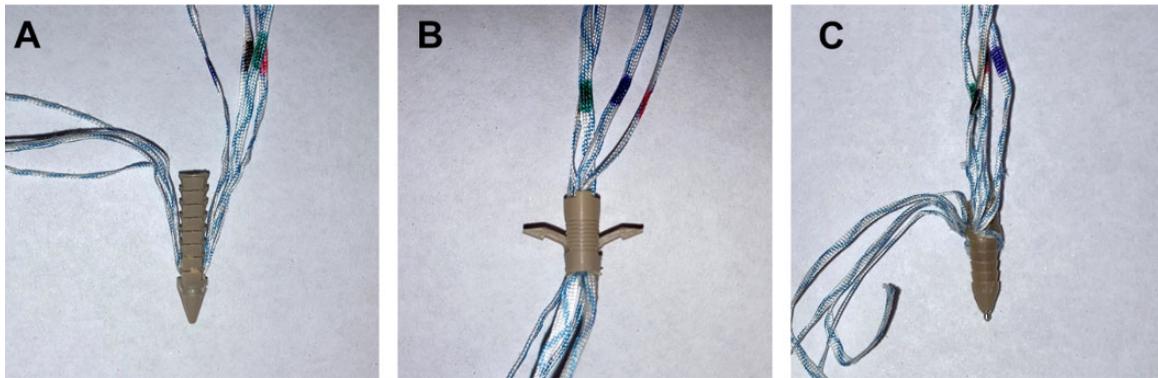


Figure 1. The internal knotless suture anchors that were tested. (A) Spiral core clamping anchor (Footprint Ultra PK). (B) Winged clamping anchor (PopLok). (C) Spooling anchor (ReelX STT). Each anchor was quadruple loaded with tape-type sutures, which were marked with distinctive colors to calculate displacement during cyclic loading.

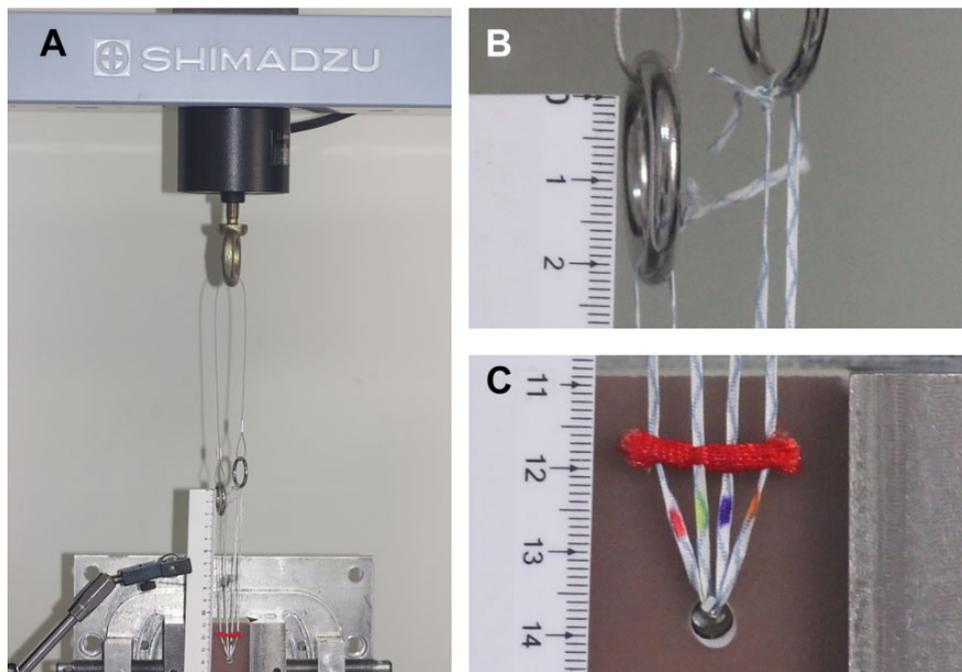


Figure 2. Setup for mechanical testing. (A) A tested construct was mounted onto the material testing system, with the sutures aligned parallel to the load actuator. (B) For the quadruple-loaded constructs, 2 steel rings interconnected with a steel cable were used to ensure equal distribution of the load. (C) Each suture limb was marked with a distinct color, which served as a reference for the extent of suture slippage. A piece of loosely braided red cotton material was put between the tape-type sutures to prevent them from closing during cyclic loading.

were connected via 2 steel rings interconnected with a steel cable. The cable passed through the metallic ring at the base of the load cell (Figure 2A). The double-loop construct ensured that the load distributed equally to the 2 steel rings, and each ring then distributed the load equally to the 2 attached suture limbs (Figure 2B).

Biomechanical Testing Protocol

The protocol comprised preloading, cyclic loading, and load-to-failure biomechanical testing. The pull-out force was

directed in a direction perpendicular to the anchor. The preloading stage began with gradual tensioning of the sutures at 0.5-mm/s intervals until a preload of 10 N was achieved.^{9,37} Preloading at 10 N persisted for 5 seconds before completion. Afterward, the cyclic loading stage began with loading between 10 and 20 N at 0.25 Hz for 50 cycles. After every 50 cycles, the maximum load was increased incrementally by 10 N. The cyclic loading stage was concluded by either the completion of 50 cycles between 10 and 90 N or pullout of any suture, as described in previous studies.⁹ The loading protocol simulated

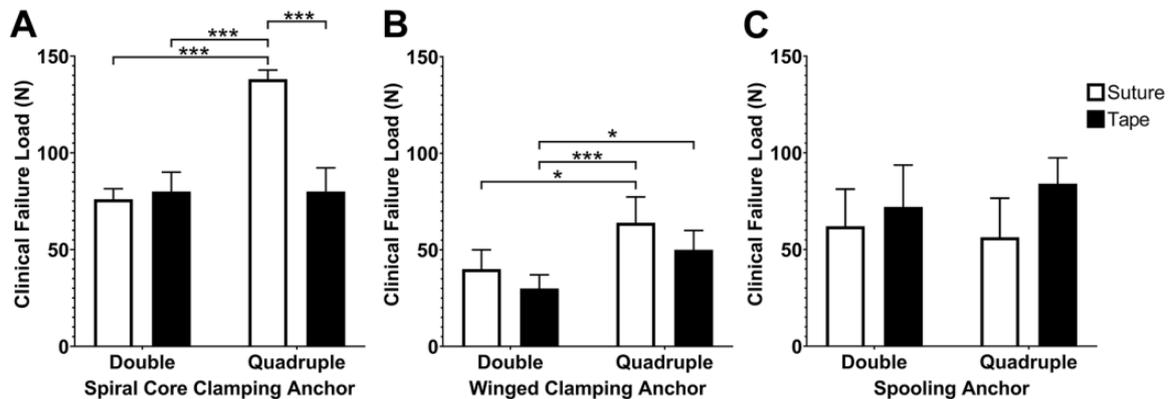


Figure 3. The clinical failure load (CFL) of the constructs tested. (A) Spiral core clamping anchor–based constructs (Footprint Ultra PK). (B) Winged clamping anchor–based constructs (PopLok). (C) Spooling anchor–based constructs (ReelX STT). The CFLs of these constructs are presented as histogram plots and grouped by the number of sutures loaded. The error bars represent the standard deviation. Statistically significant difference with 1-way analysis of variance and the post hoc Tukey test: *** $P < .001$ and * $P < .05$.

supraspinatus loading during activities of daily living. Gausden et al¹¹ showed that the supraspinatus generates less than 90 N of force in 8 of 10 common daily activities. The eventual load-to-failure stage began in specimens that had completed all 8 rounds of cyclic loading. The material testing system tensioned the constructs at a speed of 0.5 mm/s until any of the sutures pulled out.

The 3 stages were recorded, and the videos were analyzed by another investigator, who was blinded to the type of anchor. The clinical failure load (CFL), which was defined as slippage of the suture limb of ≥ 3 mm per Burkhart et al,³ was identified and documented.^{5,27}

Statistical Analysis

Data are presented as means \pm standard deviations. Before proceeding to the parametric tests, the Shapiro-Wilk test was performed to ensure that the data were normally distributed. To estimate the sample size required in the current study, a pilot study comparing the CFLs of the 4 constructs of the spiral core clamping anchor was performed. An a priori power analysis was conducted using G*Power.¹⁰ An effect size of 1.29 was calculated from the pilot study. With an alpha of 0.05 and a power of 0.90, the estimated sample size required to study 1 anchor was approximately 16 ($n = 4$ for each construct). The sample size for each anchor was ultimately set at 20, as adopted in a prior biomechanical study.³⁷ To examine our hypothesis, 1-way analysis of variance (ANOVA) and a post hoc Tukey test were conducted to compare the effects of the different constructs on each anchor. All data in this study were analyzed using SPSS version 25 (IBM).

RESULTS

There were 4 constructs tested for each type of internal knotless anchor, such that 12 constructs were tested.

Overall, 5 specimens were tested for each construct, such that 60 total constructs were tested.

Spiral Core Clamping Anchor

The 1-way ANOVA revealed a significant difference among the 4 spiral core clamping anchor constructs ($P < .001$). The 5 quadruple-loaded spiral core clamping anchor–based conventional suture constructs were the only 5 specimens to pass cyclic loading testing and progress to load-to-failure testing. The CFLs of the 4 constructs were 76.00 ± 5.48 N (double-loaded conventional), 80.00 ± 10.00 N (double-loaded tape type), 138.10 ± 4.73 N (quadruple-loaded conventional), and 80.00 ± 12.25 N (quadruple-loaded tape type) (Figure 3A). The post hoc Tukey test revealed that the CFL of the quadruple-loaded tape-tape suture construct was significantly lower than that of the quadruple-loaded conventional suture construct ($P < .001$). The CFLs of the double-loaded tape-type and double-loaded conventional suture constructs were not significantly different.

Winged Clamping Anchor

The 1-way ANOVA revealed a significant difference among the 4 constructs using the winged clamping anchor ($P < .001$). The CFLs of the 4 constructs were 40.00 ± 10.00 N (double-loaded conventional), 30.00 ± 7.07 N (double-loaded tape type), 64.00 ± 13.41 N (quadruple-loaded conventional), and 50.00 ± 10.00 N (quadruple-loaded tape type) (Figure 3B). The post hoc Tukey test revealed no significant differences in the CFLs of the quadruple-loaded tape-type suture construct and the quadruple-loaded conventional suture construct. The CFLs of the double-loaded tape-type suture construct and the double-loaded conventional suture construct did not differ significantly either. Other post hoc comparisons revealed that the CFL of the quadruple-loaded conventional suture construct was significantly higher than that of the double-loaded conventional suture construct ($P = .01$), and the CFL of

the quadruple-loaded tape-type suture construct was also significantly higher than that of the double-loaded tape-type suture construct ($P = .03$). These findings indicate that doubling the number of loaded suture materials effectively enhanced the CFL of a winged clamping anchor-based construct.

Spooling Anchor

The 1-way ANOVA revealed that the differences among the CFLs of the 4 constructs using the spooling anchor did not reach statistical significance ($P = .14$). One of the quadruple-loaded spooling anchor-based conventional suture constructs passed cyclic loading testing and progressed to load-to-failure testing. The CFLs of the 4 constructs were 62.00 ± 19.23 N (double-loaded conventional), 72.00 ± 21.68 N (double-loaded tape type), 56.32 ± 20.20 N (double-loaded tape type), and 84.00 ± 13.42 N (quadruple-loaded tape type) (Figure 3C). Alterations in suture materials or suture numbers did not have a significant impact on the CFLs of the spooling anchor-based constructs.

DISCUSSION

In this study, the replacement of suture materials and the addition of the number of sutures had contingent effects on the CFL, depending on the type of suture anchor used. With the quadruple-loaded spiral core clamping anchor, substituting tape-type sutures for conventional sutures resulted in a significant reduction of the CFL. With the winged clamping anchor-based and spooling anchor-based constructs, in contrast, the swapping of suture materials did not have a significant impact on the failure load. On the other hand, loading 4 instead of 2 conventional sutures onto spiral core clamping anchors and winged clamping anchors did increase the CFL.

During arthroscopic or open surgical repair of tendons, both double- and quadruple-loaded internal knotless anchor constructs are frequently used. The clinical significance of the current biomechanical study is that replacing conventional sutures with tape-type sutures does not always preserve the CFL for quadruple-loaded knotless anchor-based constructs. When multiple tape-type sutures are used in conjunction with a clamping anchor, clinicians should keep in mind that the CFL may not increase significantly as expected.

Internal knotless anchors are versatile and applicable for repairing various tendons. These anchors prevent sutures from directly abrading against the bone, thereby avoiding the possibility of suture cutting through the bone and resultant fixation failure observed with external knotless anchors.^{27,37} However, the CFLs of the internal knotless anchor-based constructs tested in the current study were not always sufficient for postoperative rehabilitation. During common activities of daily living, the maximal force generated by the supraspinatus ranges from 67 ± 6 to 125 ± 8 N, and that generated by the subscapularis ranges from 3 to 43 N.¹¹ When it comes to Achilles tendon repair, initial passive ankle flexion and ambulation in a cam walker with

and without the use of a 1-inch heel lift put tension of approximately 100, 190, and 369 N, respectively, onto the repaired tendon.^{1,22,28} Rehabilitation of repaired quadriceps tendons places a maximal load ranging from 100 to 250 N.^{12,31} The CFLs for the constructs tested in this study ranged from 30.00 to 138.10 N, implying that the constructs were not always adequately strong. Furthermore, the CFLs of the tape-type-based constructs ranged from 30.00 N to only 84.00 N. Owing to the fact that early rehabilitative protocols for repaired Achilles tendons and repaired quadriceps tendons often produced tension over 100 N, replacing quadruple-loaded spiral core clamping anchor-based conventional suture constructs with quadruple-loaded spiral core clamping anchor-based tape-type suture constructs should be avoided, considering the inferior CFLs obtained with the latter (138.10 ± 4.73 vs 80.00 ± 12.25 N, respectively) in the current study. To conclude, some tendon repair procedures are so demanding that the CFLs of internal knotless anchors are inadequate. Before replacing conventional sutures with tape-type sutures, it should be kept in mind that the CFLs do not increase significantly as expected under certain circumstances.

Although the data from different studies could not be compared directly, the data acquired in the present study were generally consistent with those in previous studies on this topic. Wieser et al³⁵ tested the failure loads of the same spiral core clamping anchor and a winged clamping anchor, both loaded with 2 conventional sutures. The failure loads were 88 and 66 N, respectively, in their study and were 76.00 and 40.00 N, respectively, in the current study. The difference in the failure loads between the results obtained by Wieser et al³⁵ and those obtained in the present study stemmed from the different definitions of the failure load. Wieser et al³⁵ defined maximal force (ultimate force) recorded on the force-displacement curve as the failure load, whereas in the current study, the force corresponding to the displacement of ≥ 3 mm was defined as the CFL, as proposed by Dinopoulos et al⁸ and Zhao et al.³⁸ The definition based on a ≥ 3 -mm displacement was also adopted by Burkhart et al.³

Substituting tape-type sutures for conventional sutures had a contingent effect on the suture-holding strength, and we speculate that the contingency resulted from interactions between the friction properties of the suture materials and the fixation mechanism of the knotless anchors. The braiding, coating, and shape of the suture materials all influence the frictional properties of suture materials.^{7,36} Deranlot et al⁷ found that FiberTape had less abrasive effects in comparison with FiberWire. They attributed the difference to the distinct shapes of the materials because both suture materials comprised the same core material and coating.⁷ We infer that the reduced abrasiveness found for tape-type sutures led to lower static friction at the tape-anchor interface, which presented as reduced CFLs. This inference is also reasonable for the spooling anchor-based constructs. The spooling anchor relied on the torque provided by its internal ratcheting mechanism to retain the suture, meaning its suture-holding strength did not hinge on the frictional force achieved at the suture-anchor interface.¹⁹ Therefore, substituting or doubling loaded suture materials should

have a minor impact on the CFLs of spooling anchors, as observed in the current study. In brief, we believe that the lower abrasiveness of tape-type sutures accounted for the reduction of CFLs with the quadruple-loaded spiral core clamping anchor-based constructs.

Not only did the internal knotless anchors interact differently with distinct suture materials, but they also interacted differently when doubling the number of loaded sutures. Shi et al³³ reported that a higher number of conventional sutures is correlated with a higher ultimate failure load in a meta-regression analysis of cadaveric studies. However, tape-type suture-based constructs were not analyzed in their study. Our results indicate that doubling the number of tape-type sutures did not always produce the same outcomes as doubling conventional sutures. For example, the CFL of the quadruple-loaded winged clamping anchor-based tape-type suture construct was strengthened compared with that of the double-loaded tape-type suture construct (50.00 ± 10.00 vs 30.00 ± 7.07 N, respectively). In contrast, the CFL of the quadruple-loaded spiral core clamping anchor-based tape-type suture construct was not significantly different from that of the double-loaded tape-type suture construct (80.00 ± 12.25 vs 80.00 ± 10.00 N, respectively). The clinical implication of these observations is that doubling tape-type sutures did not always increase the CFLs for knotless anchor-based constructs. Surgeons should be cautious about loading ≥ 4 tape-type sutures onto clamping anchors because these anchors were not initially designed to hold so many sutures, such that interdigitation of sutures might result. Although more sutures produce a higher normal force, the lower frictional coefficient at the suture-suture interface compared with that at the suture-anchor interface may offset the anticipated increase in CFLs.

Limitations

There are some limitations in this study. First, the current biomechanical study only examined immediately postoperative failure loads. The study design could not cover tendon-to-bone healing or other biological factors. Second, tendons repaired using knotless anchors had to endure loading from various angles. The fixed angle adopted in our design may have led to the overestimation of the failure loads. Third, the current study is only a comparative model and may not reflect the strength of these constructs in vivo.

CONCLUSION

Substituting tape-type sutures for conventional sutures did not increase the CFLs of some internal knotless anchors. With specific suture-anchor combinations, quadruple-loaded conventional suture anchors had CFLs higher than those of double-loaded conventional suture anchors.

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