Original Article

High-Tensile Strength Tapes Show Greater Ultimate Failure Load and Less Stiffness Than High-Tensile Strength Sutures in a Subpectoral Biceps Tenodesis Porcine Model

Chih-Kai Hong, M.D., Wei-Ren Su, M.D., M.Sc., Fa-Chuan Kuan, M.D., Yueh Chen, M.D., M.Sc., Chen-Hao Chiang, M.D., and Kai-Lan Hsu, M.D.

Purpose: To compare the biomechanical properties of high-tensile strength tape and a high-tensile strength suture in subpectoral biceps tenodesis using a suture anchor in a porcine tendon model. **Methods:** A total of 24 artificial composite (polymer and glass fiber) humeri and porcine flexor profundus tendons were used. Two types of suture materials, high-tensile strength sutures (group S) and high-tensile strength tapes (group T), were evaluated. After we inserted metallic suture anchors with either 2 sutures or tapes 5 cm from the superomedial corner of the greater tuberosity, a Krackow suture technique was used to secure the tendons. After a preload of 5 N for 2 minutes, a cyclic loading test from 5 to 70 N was conducted for 500 cycles. Finally, the specimen was loaded to failure at a rate of 1 mm/s. **Results:** There were no significant between-group differences in elongation after cyclic loading and elongation at failure load for group S and group T ($P = .977$ and .630, respectively). The ultimate failure loads in group T (278.2 ± 54 N) were significantly greater than those in group S (249.4 ± 32 N) ($P = .028$). In contrast, the stiffness values in group T (28.5 ± 4.0 N/mm) were significantly lower than those in group S (32.3 ± 4.5 N) ($P = .028$). Ten specimens in group S and 8 specimens in group T failed, with tendons being cut through by the sutures, whereas the other 2 specimens in group S and 4 specimens in group T failed due to suture breakage. **Conclusions:** Using high-tensile strength tapes in subpectoral biceps tenodesis using a suture anchor leads to significantly greater ultimate failure load as compared with using high-tensile strength sutures in a porcine model. Although lower levels of stiffness were found in high-tensile strength tape group, the difference in the means were not large between 2 groups. **Clinical Relevance:** A strong suture−tendon structure may prevent clinical failure of a subpectoral biceps tenodesis using a suture anchor.

Lesions of the long head of the biceps brachii (LHB) tendon can possibly lead to anterior shoulder pain and shoulder dysfunction.[1,2] Both biceps tenotomy and tenodesis are considered to be effective treatments for symptomatic LHB pathology.[3-7] Recently, biceps tenodesis has become popular,[8] and members of the American Shoulder and Elbow Society seem to favor biceps tenodesis over tenotomy.[9] Among various tenodesis techniques, open subpectoral biceps tenodesis remains a well-liked option because it features several advantages, including simplicity, direct visualization, and prevention of length−tension relation mismatch.[10-12] Recently, some authors have promoted the use of suture anchors in biceps tenodesis since they have been found to result

From the Department of Orthopaedic Surgery (C.-K.H., W.-R.S., F.-C.K., K.-L.H.) and Skeleton Materials and Bio-compatibility Core Lab, Research Center of Clinical Medicine (W.-R.S.), National Cheng Kung University Hospital, College of Medicine, National Cheng Kung University, Tainan; Department of Biomedical Engineering (F.-C.K., K.-L.H.), National Cheng Kung University, Tainan; Department of Orthopaedic Surgery, Sin Lau Hospital, Tainan (Y.C.); and Department of Orthopaedic Surgery, Chiayi Christian Hospital, Chiayi (C.-H.C), Taiwan.

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Address correspondence to Kai-Lan Hsu, M.D., Department of Orthopaedic Surgery, National Cheng Kung University Hospital, College of Medicine, National Cheng Kung University, No. 138, Sheng-Li Rd, Tainan City, Taiwan 70428. E-mail: dulendulen@gmail.com

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in less anatomical failure[13] and may reduce some possible complications, such as tendon damage or humeral fracture.[10,14]

The structure at the suture–tendon junction will greatly affect the biomechanical properties of biceps tenodesis when using a suture anchor.[15-17] Previous biomechanical studies focused on the suture techniques for fixing these tendons using suture anchors and indicated that more complex suture techniques, such as the Krackow suture technique, may significantly increase the ultimate failure loads of the tenodesis constructs.[15-17] However, despite the use of the Krackow suture, the common failure mechanism of tenodesis using a suture anchor has remained failure at the tendon–suture interface, including tendon split by sutures or suture rupture.[14,16]

A high-tensile strength tape has the potential to enhance the tendon–suture interface in the biceps tenodesis structure using a suture anchor. This kind of high-tensile strength tape contains ultra-high molecular weight polyethylene over the entire tape without a central core, which was developed to avoid tendon cut through by solid core sutures.[18] Leishman and Chudik[18] reported that this high-tensile strength tape has greater knot security, ultimate load to failure, and tensile stiffness than a high-tensile strength round core suture.

Although the high-tensile strength tape has a greater ultimate failure load as compared with the high-tensile strength suture and could possibly lead to less tendon cut through,[18] little is known about its performance in subpectoral biceps tenodesis using a suture anchor. The purpose of this study is to compare the biomechanical properties of high-tensile strength tape and a high-tensile strength suture in subpectoral biceps tenodesis using a suture anchor in a porcine tendon model. We hypothesized that the high-tensile strength tape would have significantly greater ultimate failure load and stiffness as compared with the high-tensile strength suture in subpectoral biceps tenodesis using a suture anchor.

Methods

The current study was granted an exemption from the institutional review board in a medical center. The model for tenodesis biomechanical testing was in accordance with a previous study.[16]

Specimens

Fourth-generation composite humeri (model #3404; Pacific Research Laboratories, Vashon, WA) were used in this study because previous studies have suggested it to be a reliable substitute for cadaver specimens for the purpose of biomechanical testing.[19,20] It has been reported that the fourth-generation composite humerus not only reproduces the biomechanical properties of human bone but also reduces the interspecimen variability that occurs with cadaveric bone.[19,20] Finally, a total of 24 large-size, left, fourth-generation composite humeri were used. The humerus was cut at mid-level of the shaft with a saw, and the proximal part of the humerus was preserved. The tenodesis site was located 5 cm distal from the superomedial corner of the greater tuberosity.[16,21]

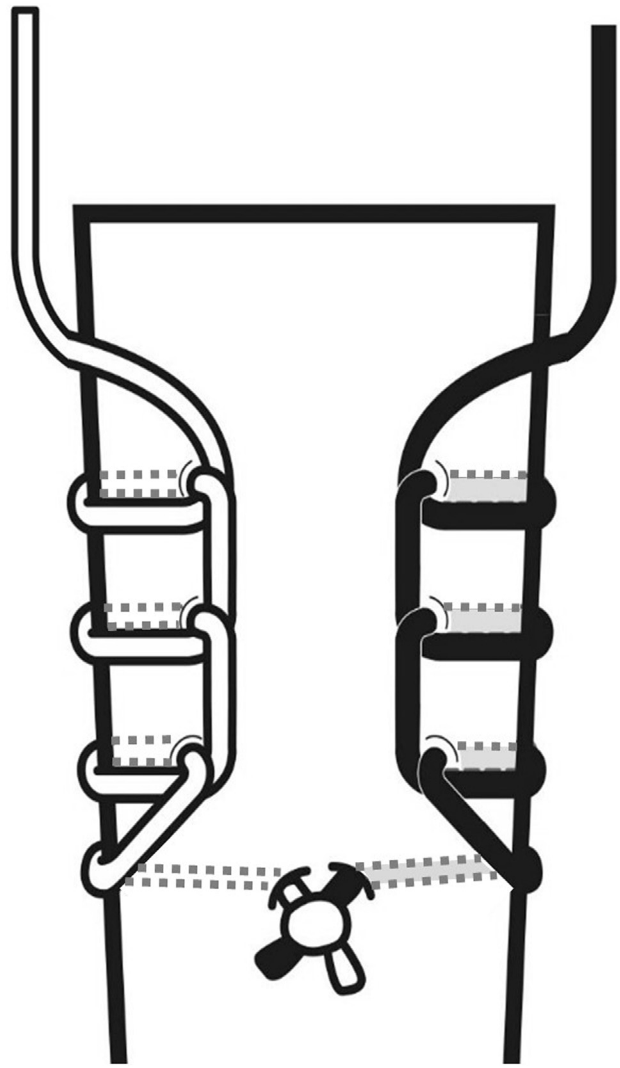

Fig 1. The illustration of Krackow suture technique from Arena and Dhawan.[10]

A total of 24 porcine flexor foreleg tendons from fresh adult male porcine (mean age, 22 months) were chosen to simulate the LHB tendons because a previous study indicated that porcine flexor tendons have similar biomechanical properties to those of human cadaveric tendons.[22] The trotters were stored at −20° and were thawed to room temperature before dissection. The quality of the tendon was assessed by a single author (C.-K.H.). Next, after removal of the attached soft tissue, the entire flexor tendon was harvested. A sizer was used for the preliminary selection to confirm the size of the tendon to be approximately 4.5 mm, since the average diameter of LHB tendon has been reported to be

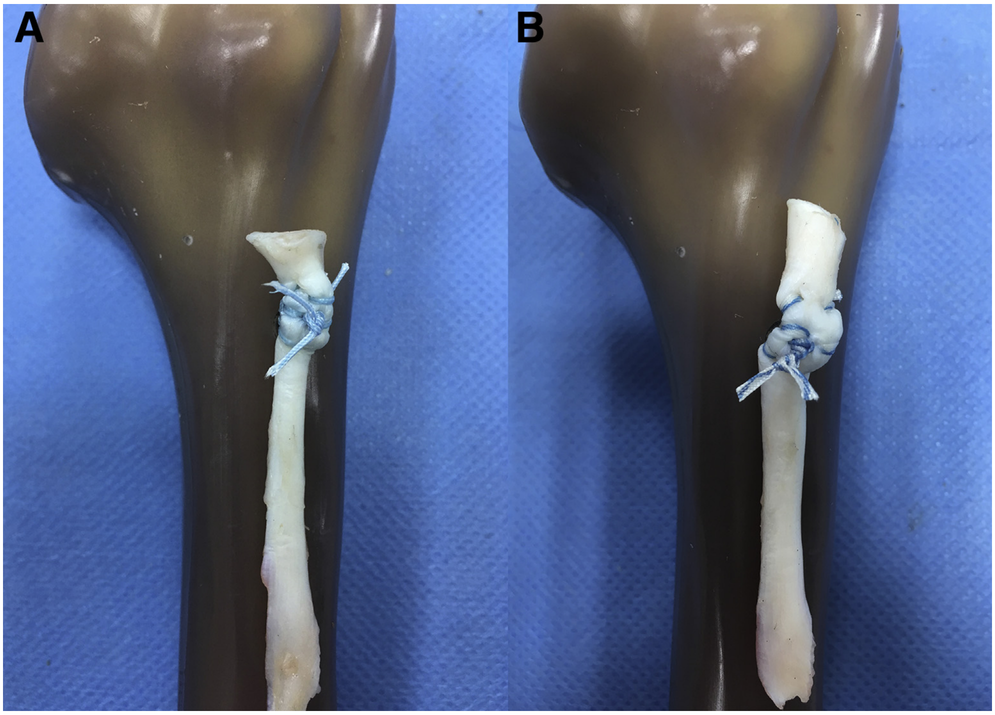

Fig 2. Illustration of subpectoral biceps tenodesis constructs using suture anchors with (A) high-tensile strength sutures and (B) high-tensile strength tapes in left humerus composite bones.

4.4 mm, ranging from 3.5 to 5.0 mm.[23] Subsequently, the actual cross-sectional area of each tendon was measured with the use of a calibration scale, a digital camera, and image processing software (ImageJ, version 1.52p; National Institutes of Health, Bethesda, MD).

With a use of a random numbers table, the composite humeri and porcine flexor tendons were randomly divided into 2 groups: a high-tensile strength suture group (group S) and a high-tensile strength tape group (group T).

High-Tensile Strength Suture Group (Group S)

Metallic suture anchors (Corkscrew Suture Anchor, 5.0 mm; Arthrex, Naples, FL) with double-loaded No. 2 high-tensile strength sutures (FiberWire; Arthrex) were used. The suture anchors were inserted at 90° to the bone surface at the tenodesis site until the eyelets of the suture anchors were at level with the bone.

High-Tensile Strength Tape Group (Group T)

Metallic suture anchors (Corkscrew Suture Anchor, 5.0 mm; Arthrex) were used for the tenodesis. Before the insertion of the anchor, the high-tensile strength sutures from the suture anchor were substituted with two high-tensile strength tapes (1.3-mm SutureTape; Arthrex). The suture anchors were inserted at 90° to the bone surface at the tenodesis site until the eyelets of the suture anchors were level with the bone.

Suture Technique

The suture technique for LHB tendon fixation followed the method from Arena and Dhawan.[10] Starting 1.0 cm from the tendon end, 1 suture strand was used to run 3 locking stitches in a Krackow configuration on the lateral aspect of the tendon, whereas the other suture strand was sutured in the same fashion along the medial aspect of the tendon. Next, the 2 running sutures were tied together with half hitches (Fig 1). Then, the 2 remaining free ends of the sutures were passed through the tendon from the posterior-to-anterior direction with one located at the proximal Krackow loop and the other at the distal Krackow loop. After these 2 suture ends are pulled, the tendon was attached to the tenodesis site on the humerus. Finally, the 2 sutures were tied together with 5 half hitches to secure the tendon on the tenodesis site (Fig 2).

Testing Setup

The prepared specimens were mounted in the material testing machine (AG-X; Shimadzu, Tokyo, Japan) for biomechanical testing (Fig 3). The humeral head of the composite bone was fixed via a customized jig connected to the base of the material testing machine. Another custom-made sinusoidal clamp, connected to the test actuator and an inline 1000-N load cell, was used to secure the porcine tendon 10 cm from the tendon end. To ensure that the direction of the tensile force on the tendons was parallel to the longitudinal axis of the humerus, an X-Y table allowed the adjustment of the position of the construct.

The biomechanical testing protocol comprised pretensioning, cyclic loading, and load-to-failure tests. Each specimen was first preloaded to 5 N for 2 minutes.

Fig 3. The experimental setup for biomechanical testing. The composite artificial humerus was mounted on the material testing machine with a customized securing device (yellow arrow), and the porcine flexor tendon was secured with a sinusoidal clamp (white arrow) which was connected to the load cell. Vertical cyclic and failure forces were applied.

Next, cyclic loading force from 5 to 70 N was given for 500 cycles. Finally, the specimen was loaded to failure at a constant crosshead rate of 1 mm/s. The aforementioned parameters were consistent with those in previous studies.[14,16,24-27]

During testing, the relevant parameters, including testing time, force, and actuator displacement, were recorded using Trapezium X software (version 1.00; Shimadzu, Tokyo, Japan). Displacement at cyclic loading could be acquired by calculating the difference between the actuator displacement in the first cycle at 5 N and that in the 500th cycle at 70 N. The displacement at failure was calculated based on the peak displacement at the failure load and the initial preconditioned load at 5 N in the load-to-failure test. The yield point in the stress—strain curve was identified during load-to-failure test. The stiffness for the elastic region in the stress—strain curve calculated using the data of applied force and the displacement of whole construct. The failure mode of each specimen was recorded after the load-to-failure test.

Statistical Analysis

The required sample size for this biomechanical study was determined based on a pilot study with a total of 8 specimens randomly assigned to 2 groups (group S and group T) using G*Power, version 3.1.3 software (Heinrich Heine-University of Dusseldorf, Dusseldorf, Germany). An α equal to 0.05 and a power ($1 - \beta$) of 0.80 were given to this pilot study model, and an effect size of 1.44 was obtained. Accordingly, a required sample size of 20 specimens was determined to be appropriate. We finally included 24 samples in total, with 12 in each group.

SPSS software for Windows (version 20.0; IBM Corp., Armonk, NY) was used for the statistical analysis. Descriptive statistics, including means and standard deviations, were obtained for both groups. The Mann—Whitney *U* test was used to compare the ultimate failure load, stiffness, the elongation after cyclic loading, and elongation at failure load between the 2 groups. A χ^2 test was used to compare the failure modes between 2 groups. The statistical significance was set as $P \leq .05$.

Results

The cross-sectional areas of the flexor tendons of the forelegs in group S (15.9 ± 0.5 mm^2) and group T (15.8 ± 0.6 mm^2) were not significantly different ($P = .713$). All specimens in groups S and T completed the cyclic loading tests as well as the load to failure tests.

The biomechanical testing results are concluded in Table 1. There were not significant between-group differences in the elongation after cyclic loading and elongation at failure load ($P = .977$ and .630, respectively).

Table 1. Results of Biomechanical Testing Between High-Tensile Strength Suture Group (Group S) and High-Tensile Strength Tape Group (Group T)

Variables (Mean ± SD)	Group S (n = 12)	Group T (n = 12)	*P* Value
Cyclic elongation, mm	5.9 ± 1.4	5.8 ± 1.1	.977
Failure elongation, mm	10.9 ± 2.5	10.5 ± 2.9	.630
Ultimate failure load, N	249.4 ± 32	278.2 ± 54	.028*
Stiffness, N/mm	32.3 ± 4.5	28.5 ± 4.0	.028*
Failure mode	10 tendon tears 2 suture breakages	8 tendon tears 4 suture breakages	.320

SD, standard deviation.
*Significant between-group differences with the Mann—Whitney *U* test.

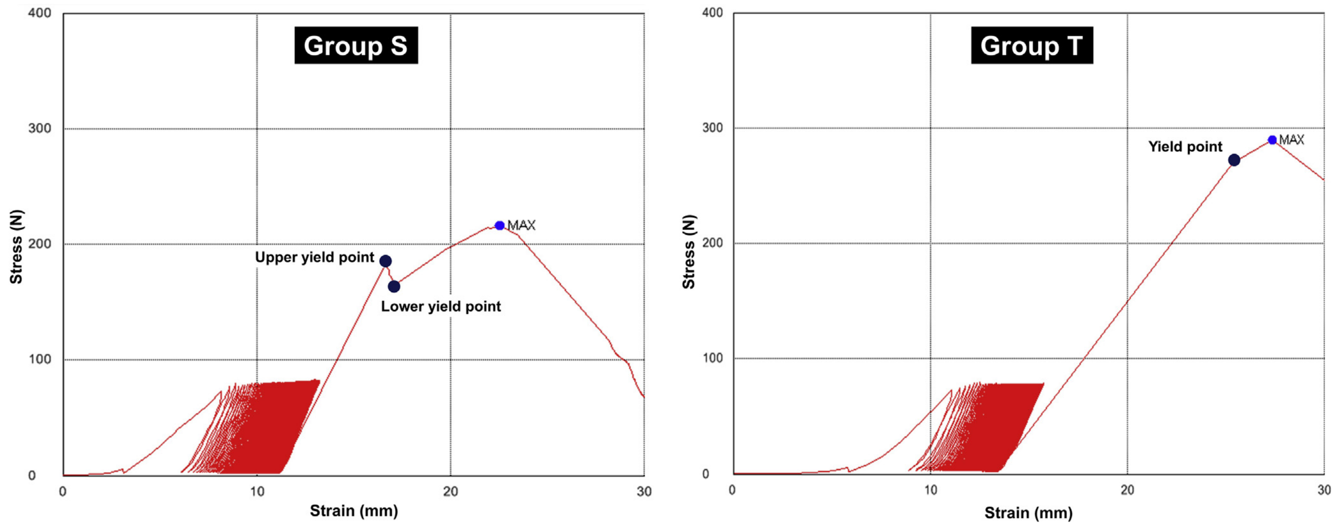

Fig 4. Strain—stress curves of group S and group T. The yield point and failure point with maximal force are marked.

The ultimate failure loads in group T (278.2 ± 54 N) were significantly greater than those in group S (249.4 ± 32 N) ($p = 0.028$). On the contrary, the stiffness values in group T (28.5 ± 4.0 N/mm) were significantly smaller than those in group S (32.3 ± 4.5 N) ($P = .028$).

The strain—stress curves of group S and group T were illustrated in Figure 4. In group S, both the upper and lower yield points existed, and there was a flat curve between lower yield point and the maximal stress point. In group T, only a yield point was found, and the distance between the yield point and the maximal stress point was short. The slope of linear portion in the stress—strain curve up to the yield point represented the stiffness.

In group S, 10 of 12 specimens failed due to the tendon being cut through by the sutures, whereas suture breakage at the tendon—suture interface was found in the remainder of the specimens (2/12). In group T, 8 of 12 specimens failed due to a tendon tear, whereas suture breakage occurred in the rest of the specimens (4/12). No anchor pull-out from the humerus was identified in all specimens.

Discussion

The principal findings of this study indicated that using high-tensile strength tapes in subpectoral biceps tenodesis using a suture anchor leads to significantly greater ultimate failure load but lower levels of stiffness as compared with using high-tensile strength sutures. Open subpectoral biceps tenodesis is popular,[9] and using suture anchors in open subpectoral biceps tenodesis has been promoted, since some possible complications can be avoided.[10,14] Among the different suture techniques in subpectoral biceps tenodesis using a suture anchor, the Krackow suture technique has been shown to have superior biomechanical properties.[16,17] In addition, a high-tensile strength tape has been developed. It features a greater ultimate failure load than the high-tensile strength suture and has the potential to decrease tendon cut through.[18] Our study thus further evaluated the use of high-tensile strength tapes in subpectoral biceps tenodesis using a suture anchor. Unfortunately, the results of our study did not entirely fit the proposed hypothesis. Despite of this, the difference in the means in stiffness was not large.

Using tape-type sutures has the potential to enhance biomechanical structure in biceps tenodesis using a suture anchor. Ono et al.[28] indicated that tape-type sutures may be protective in terms of sutures pulling through tendon during loading since tape-type sutures enlarge the suture holes less and displace less than standard no.2 sutures after repetitive tractions. Similarly, Leishman and Chudik reported that a high-tensile strength tape, SutureTape, has better knot security and greater ultimate load to failure than FiberWire, a no. 2 high-tensile strength suture.[18] Therefore, it was reasonable to expect a significantly greater ultimate failure load in the SutureTape group than in the FiberWire group in the present study.

It is interesting to notice that the group S had significantly greater stiffness values than the group T, although the ultimate failure load in group T was significantly greater than the group S, and the failure elongation were similar in 2 groups. The aforementioned findings could be explained from the stress—strain curve in 2 groups. In the present study, the stiffness was calculated by the slope of linear portion in the elastic region in the stress-strain curve. Take Figure 4 as an example; a steep slope could be found in the group S, whereas the slope of linear curve in the group T was relative flat. However, the displacements after yield points were different between the 2 groups. In the group T, the failure point was close to the yield point; in the group S, however, both upper and lower yield points existed, and the curve between yield point and failure point was flat, resulting in greater failure displacement.

Stiffness is a structural property; the shape of a stiff structure changed only slightly under elastic loads. The present study found significantly greater stiffness values in the S group as compared with the T group. The aforementioned finding was unexpected since the previous study reported that tape-type sutures (FiberTape, Arthrex) had significantly greater stiffness values than no. 2 sutures (FiberWire, Arthrex) in a sheep infraspinatus tendon model.[28]

Some possibly factors may play roles in these differences. The first factor was the tendons in small size (approximately 4.5 mm in width) in this study that were different from the previous study[28] using tendons 10 mm in width. As tape-type sutures created larger hole volumes through the tendon than standard No. 2 sutures (3.0 mm^2 vs 1.8 mm^2),[28] we thus infer that this larger defect may especially compromise the suture–tendon interface in smaller tendons. Other factors, such as knot security of different suture materials, may also contribute to the difference.

Our biomechanical testing, results were generally consistent with those of previous studies. Hong et al.[16] conducted a biomechanical study for subpectoral biceps tenodesis and found a mean failure loads of 283.5 N for the Krackow suture technique group. Despite different sutures obtained from different companies, the mean ultimate failure loads in our study were at similar levels, 257 N and 295 N in group S and group T, respectively. In contrast, Hong et al.[16] reported tendon being cut through by the sutures as well as suture breakage at the tendon–suture interface as possible failure modes for the Krackow suture technique group. Comparably, both of these types of failure modes were observed in the present study.

Limitations

There are some limitations in this study. First, the healing process and effects of postoperative rehabilitation could not be fully simulated in this ex vivo time-zero biomechanical study. Second, artificial humeri and porcine tendons were used in this study, rather than cadaveric specimens. Despite the different structures, previous studies have suggested that both artificial humeri[19,20] and porcine tendons[22] are eligible surrogates for cadaveric specimens. In addition, since the quality of artificial humeri and porcine tendons were controlled, the effects of different suture materials on the fixation strength could be better evaluated than would be the case otherwise. Lastly, the results from this study can only be applied to the assessed technique, the Krackow suture technique.

Conclusions

Using high-tensile strength tapes in subpectoral biceps tenodesis using a suture anchor leads to significantly greater ultimate failure load as compared with using high-tensile strength sutures in a porcine model. Although lower levels of stiffness were found in high-tensile strength tape group, the difference in the means were not large between 2 groups.

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