Knots Tied With High–Tensile Strength Tape Biomechanically Outperform Knots Tied With Round Suture

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Background: Tape-type suture material is well-accepted in arthroscopy surgery.

Purpose: To compare the knot security of a high–tensile strength round suture and high–tensile strength tape with commonly used arthroscopic knots.

Study Design: Controlled laboratory study.

Methods: We compared the performance of No. 2 braided nonabsorbable high-strength suture with that of 1.3-mm braided nonabsorbable high-strength tape. Five commonly used arthroscopic knots were investigated: the Roeder knot; the Western knot; the Samsung Medical Center (SMC) knot; the Tennessee knot; and a static surgeon's knot. Seven knots were tied for each combination of knots and suture types. Knots were tied on a 30-mm circumferential metal post, and the suture loops were transferred to a materials testing machine. After preloading to 5 N, all specimens were loaded to failure. The clinical failure load, defined as the maximal force to failure at 3 mm of crosshead displacement, yield load, and stiffness, were recorded. A 2-way analysis of variance was used to determine differences between the groups.

Results: Both suture type and knot type significantly affected the clinical failure load, yield load, and stiffness ($P = .002$). The high-strength tape resulted in a significantly greater clinical failure load than the high-strength suture in the case of the Roeder knot, Western knot, and SMC knot ($P = .027$, .005, and .016, respectively). When the high-strength round suture was used, the Roeder knot, Western knot, and SMC knot resulted in significantly smaller clinical failure loads compared with the Tennessee knot ($P =$ .011, .003, and .035, respectively) and the static surgeon's knot ($P < .001$ for all). When the high-strength tape was used, the Roeder knot, Western knot, and SMC knot resulted in significantly smaller clinical failure loads compared with the static surgeon's knot ($P = .001$, .001, and .003, respectively).

Conclusion: The results of this study indicated that arthroscopic knots tied using 1.3-mm high-strength tape biomechanically outperformed knots tied using a No. 2 high-strength suture. While the static surgeon's knot exhibited the best biomechanical properties, the Tennessee knot resulted in generally better biomechanical properties among the arthroscopic sliding knots.

Clinical Relevance: Elongation and loosening of tied knots possibly affects the clinical results of repaired constructs.

Keywords: arthroscopy; knot; high-strength suture; high-strength tape; biomechanical

To achieve a secure construct for soft tissue healing to bone in arthroscopic rotator cuff and labral repair surgeries, arthroscopic knots are usually required. A secure knot allows the maintenance of the apposition of soft tissue to bone.[3] Knot security, which is the ability of the knot to resist slippage, depends on friction, internal interference, and the slack between throws.[2,3] Several arthroscopic sliding knots have been proposed to be adequate options based on biomechanical evaluations.[2-4,8,11-13,16,17]

In recent years, tape-type suture material (as opposed to traditional round suture material) has become increasingly popular in arthroscopic surgery. Tapes provide greater tissue contact area, which potentially increases resistance to pullout and reduces tendon pullthrough.[6,10] In terms of ultimate failure loads, Gnandt et al[6] indicated that using high–tensile strength tape with whipstitch (709 N) and Krackow suture techniques (427 N) led to significantly greater values than the use of high–tensile strength sutures with whipstitch (528 N) and Krackow suture techniques (333 N). Ono et al[14] reported similar findings suggesting that tape-type sutures had significantly greater

The Orthopaedic Journal of Sports Medicine, 9(10), 23259671211039554
DOI: 10.1177/23259671211039554

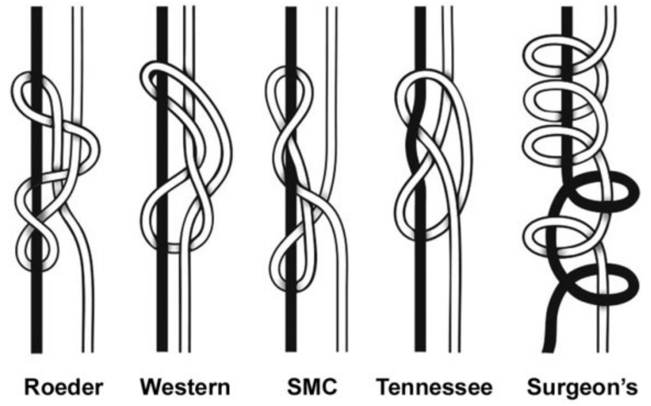

Figure 1. Illustration of Roeder knot, Western knot, Samsung Medical Center (SMC) knot, Tennessee knot, and static surgeon's knot.

stiffness than standard sutures in a sheep infraspinatus tendon repair model.

Although using tape-type suture material in arthroscopy surgeries is well-accepted, little is known about the knot security of arthroscopic sliding knots when this type of suture is used. The purpose of this study was to compare the knot security of high–tensile strength round suture and high–tensile strength tape using common arthroscopic knots. We hypothesized that high–tensile strength tape will increase the clinical failure load of arthroscopic sliding knots compared with high-tensile strength round suture.

METHODS

Two suture types were compared: a braided nonabsorbable high-strength round suture, No. 2 FiberWire (Arthrex), and a braided nonabsorbable high-strength tape, 1.3-mm SutureTape (Arthrex). Five commonly used arthroscopic knots were chosen for this investigation, including 4 popular arthroscopic sliding knots and an arthroscopic static knot (Figure 1). The selected arthroscopic knots included the Roeder knot, the Western knot, the Samsung Medical Center (SMC) knot, and the Tennessee knot. During testing, each arthroscopic knot was followed with 3 reversing half-hitches on alternating posts (RHAPs). Reversing the half-hitches and alternating the posts was performed by alternately tensioning the wrapping limbs with consecutive throws.[13] A static 6-throw surgeon's knot was also studied. The surgeon's knot consists of a stack of 3 half-hitches (base knot) followed by 3 consecutive half-hitches on alternating posts.[13]

Seven knots were tied for each possible combination of knots and suture types, for a total of 70 knots. The sample size was calculated based on clinical failure load in a pilot study, in which 30 specimens (15 using round sutures and 15 using tape-type sutures) were randomly assigned to 5 knot groups. An α equal to .05 and a power (1-β) of 0.80 were set for this a priori power analysis model, and an effect size of 0.75 was calculated from the data in a pilot study. The required sample size of at least 6 specimens in each group was consequently determined with G*Power Version 3.1.3 software (Heinrich Heine University of Dusseldorf). We chose 7 specimens per group to achieve sufficient power in the study.

All knots were tied by a single orthopaedic surgeon (C.-K.H.). To minimize potential bias, knot-tying practice sessions were arranged before tying each knot. Before knot tying, each suture was soaked in normal saline solution for at least 10 minutes.[4,8,16,17] All knots were hand tied on a 30-mm circumferential metal post[3,8,11,13,16,17] by a surgeon wearing surgical gloves (Figure 2, A and B). Removing twists, eliminating slack between throws, and tensioning the 2 suture limbs were done carefully to ensure optimal knot and loop security during knot tying. To prevent the knot from slipping backward after each knot was tied, the nonpost limb was tensioned to lock the knot in place. The completed knotted suture loop was carefully removed from the post and soaked in normal saline solution for 1 minute. Finally, the suture loop was placed in the materials testing machine.

The knots were tested using a materials testing machine (AG-X model; Shimadzu). The suture loops were mounted on a custom-made jig, which contained two 4-mm–diameter rods connected to the base and the crosshead of the materials testing machine (Figure 2C). In previous studies,[8,11,17] different sizes of rods (3.6-3.95 mm) were used for testing. In the present study, the 4-mm–diameter rod was chosen to minimize the potential effects of metal rod deformity during biomechanical testing. The biomechanical testing protocol was based on previous studies.[11-13] Each suture loop was preloaded to 5 N to remove excess slack. Then, the suture loop was pulled apart with a crosshead speed of 1

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Final revision submitted May 16, 2021; accepted May 27, 2021.

One or more of the authors has declared the following potential conflict of interest or source of funding: This study was funded by Ministry of Science and Technology and National Cheng Kung University Hospital, Tainan (NCKUH-11002049). AOSSM checks author disclosures against the Open Payments Database (OPD). AOSSM has not conducted an independent investigation on the OPD and disclaims any liability or responsibility relating thereto.

Ethical approval was not sought for the present study.

mm/s until failure. Knot slippage to 3 mm (crosshead displacement) was defined as clinical failure.[11] Clinical failure load was defined as the highest load necessary to displace the suture loop within 3 mm. The yield point was identified in the load-elongation curve, and the yield load as well as the stiffness for the elastic region in the load-elongation curve were calculated.

Statistical Analysis

Descriptive statistics, including means, standard deviations, and 95% CIs were obtained for all subgroups. Kolmogorov-Smirnov tests were used to determine data normality. The Levene test was used to assess the equality of variances for each variable. A 2-way analysis of variance (ANOVA; knot and suture type) was used to determine differences between the groups for clinical failure load, yield, and stiffness. The main effects of the knots and suture types were evaluated using Tukey honestly significant difference post hoc pairwise comparison. An α level of $P < .05$ was considered statistically significant. All statistical analyses were conducted using SPSS Version 20 (IBM SPSS Inc).

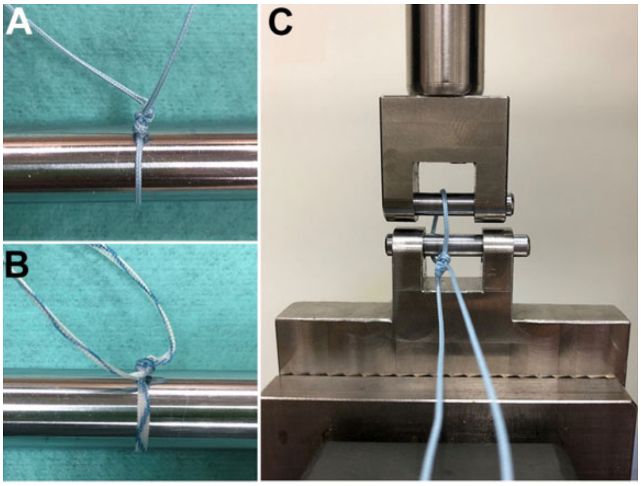

Figure 2. Illustration of knot tying and biomechanical testing setup. (A) The round suture and (B) tape-type suture were tied on a 30-mm circumferential metal post. (C) The completed suture loop was placed in a custom-made jig, which comprised two 4-mm–diameter rods connected to the base and the crosshead of the materials testing machine.

RESULTS

All constructs failed owing to 3-mm crosshead separation without suture breakage. The mean values of clinical failure load, yield load, and stiffness in each group are summarized in Table 1.

The Kolmogorov-Smirnov tests showed that the study data for clinical failure load, yield load, and stiffness were all normally distributed (P = .200, .200, and .066, respectively). The results of the Levene test showed homogeneity of variance for clinical failure load, yield load, and stiffness (P = .127, .111, and .150, respectively). The results of the 2-way ANOVA showed no interaction between knot and suture type for clinical failure load, yield load, or stiffness (P = .833, .380, and .066, respectively) (Table 2). Both suture type and knot type significantly affected the clinical failure load ($P < .001$ for both), yield load (P = .002 and .001, respectively), and stiffness ($P < .001$ for both).

In the pairwise comparisons for clinical failure loads (Figure 3), the tape suture was found to have significantly greater clinical failure loads than the round suture in the case of the Roeder knot, Western knot, and SMC knot (P = .027, .005, and .016, respectively). When comparing knots tied with round sutures, the Roeder knot, the Western knot, and the SMC knot had significantly smaller clinical failure loads compared with the Tennessee knot (P = .011, .003, and .035, respectively) and the static surgeon's knot ($P < .001$ for all); meanwhile, the Tennessee knot had significantly smaller clinical failure loads

TABLE 1

The Clinical Failure Load, Yield Load, and Stiffness for Round Suture and Tape-Type Suture[a]

	Clinical Failure Load (N)		Yield Load (N)		Stiffness (N/mm)	
	Mean ± SD	95% CI	Mean ± SD	95% CI	Mean ± SD	95% CI
Suture (FiberWire)						
Roeder knot	144.9 ± 30	117.3-172.5	105.7 ± 26	81.6-129.8	75.7 ± 9.7	66.8-84.7
Western knot	134.9 ± 52	87.1-182.7	102.0 ± 50	56.1-147.9	87.6 ± 8.3	79.9-95.3
SMC knot	155.5 ± 28	129.8-181.2	119.1 ± 49	73.8-164.4	80.9 ± 16	65.8-96.0
Tennessee knot	203.3 ± 26	178.9-227.7	127.7 ± 44	87.3-168.2	97.8 ± 16	83.4-112.28
Static surgeon's knot	248.2 ± 32	218.7-277.8	212.4 ± 19	195.2-229.6	86.3 ± 11	75.7-96.9
Tape (SutureTape)						
Roeder knot	195.2 ± 50	149.3-241.1	163.1 ± 40	126.4-199.8	86.4 ± 13	74.5-98.3
Western knot	200.1 ± 65	139.6-260.6	160.0 ± 73	92.3-227.3	96.6 ± 22	75.5-117.7
SMC knot	210.5 ± 24	187.9-233.2	166.0 ± 52	118.1-213.8	89.4 ± 23	68.0-110.7
Tennessee knot	242.1 ± 40	204.9-279.3	170.8 ± 76	100.7-240.8	106.3 ± 17	90.2-112.3
Static surgeon's knot	300.2 ± 27	275.1-325.4	202.4 ± 54	164.1-260.7	125.0 ± 18	113.4-152.3

[a] SMC, Samsung Medical Center.

compared with the static surgeon's knot ($P = .047$). A comparison of the knots tied with tapes indicated that the Roeder knot, the Western knot, and the SMC knot had significantly smaller clinical failure loads compared with the static surgeon's knot ($P = .001$, .001, and .003, respectively), while the Roeder knot also had smaller clinical failure loads compared with the Tennessee knot ($P = .038$).

In the pairwise comparison for yield loads (Figure 4), the tape sutures had significantly greater yield loads than the round sutures in the Roeder knot and the Western knot ($P = .039$ and .038, respectively). In the case of the different knots tied with round sutures, the Roeder knot, Western knot, SMC knot, and Tennessee knot had significantly smaller yield loads compared with the static surgeon's knot ($P < .001$, $< .001$, .001, and .003, respectively). There were no significant differences among the groups when comparing different knots tied with tape suture.

TABLE 2

Results of 2-Way ANOVA for Group Differences[a]

	Mean Square	*F*	*P*
Clinical failure load			
Knot type	23,869.1	13.9	**<.001**
Suture type	40,535.3	23.6	**<.001**
Knot × suture	626.3	0.37	.833
Yield load			
Knot type	13,699.8	5.3	**.001**
Suture type	26,655.3	10.3	**.002**
Knot × suture	2775.1	1.1	.380
Stiffness			
Knot type	1563.4	5.93	**<.001**
Suture type	3965.3	15.0	**<.001**
Knot × suture	614.8	2.3	.066

[a] Bolded *P* values indicate statistical significance ($P < .05$; 2-way ANOVA).

ANOVA, analysis of variance.

In the pairwise comparison for stiffness (Figure 5), the tape sutures had significantly greater stiffness than the round sutures in the static surgeon's knot ($P < .001$). In the comparison of the different knots tied with round sutures, the Roeder knot had significantly less stiffness compared with the Tennessee knot ($P = .014$). In the comparison of the different knots tied with tape sutures, the Roeder knot, Western knot, SMC knot, and Tennessee knot had significantly less stiffness than the static surgeon's knot ($P < .001$, .002, $< .001$, and .035, respectively); meanwhile, the Roeder knot also had significantly less stiffness than the Tennessee knot ($P = .026$).

DISCUSSION

The major finding of the present study was that arthroscopic knots tied with a tape-type suture demonstrated significantly better biomechanical properties in our testing compared with a round suture. The Tennessee knot as well as the static surgeon's knot exhibited generally superior biomechanical properties compared with the other selected knots. The findings supported our hypothesis and supported the use of high–tensile strength tape in arthroscopic knot–based repairs.

Due to its larger surface area compared with a round suture, the tape-type suture is designed to increase resistance to tissue pull-through by providing greater tissue contact. Leishman and Chudik[10] reported that 1.3-mm high-strength tape exhibited significantly greater stiffness and ultimate load than No. 2 high-strength round suture in their isolated suture biomechanical testing. They also indicated that high-strength tape showed superior knot security with minimal slippage compared with high-strength

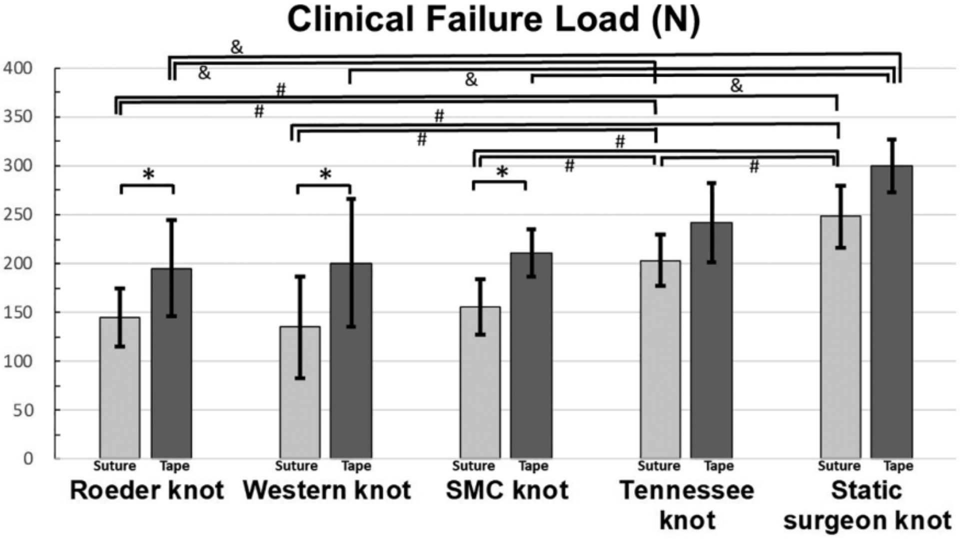

Figure 3. Clinical failure loads in each suture-knot subgroup. Statistically significant differences ($P < .05$): *between the suture and tape groups within the same knot; #between different knots tied with high-strength round sutures; and &between different knots tied with high-strength tape. SMC, Samsung Medical Center.

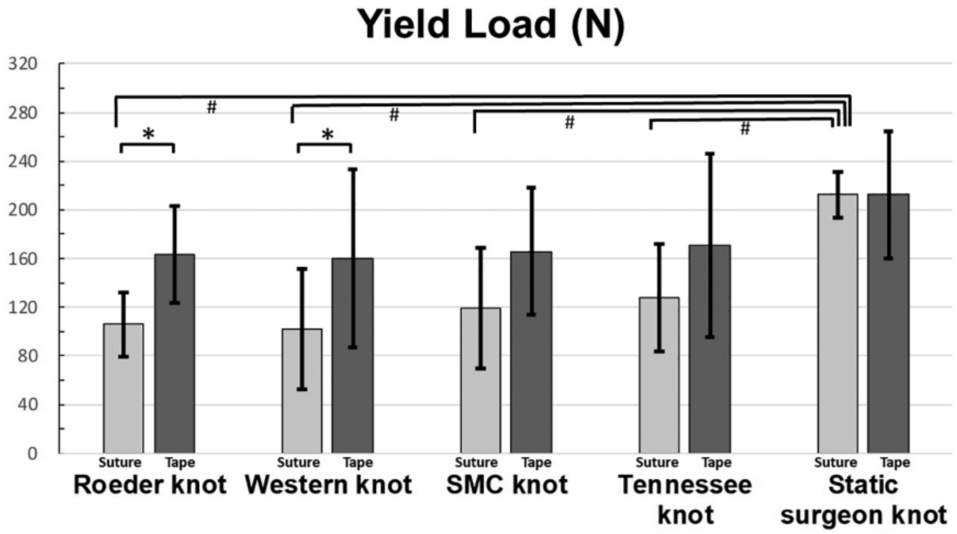

Figure 4. Yield loads in each suture-knot subgroup. Statistically significant differences ($P < .05$): *between the suture and tape groups within the same knot; and #between the different knots tied with high-strength round suture. SMC, Samsung Medical Center.

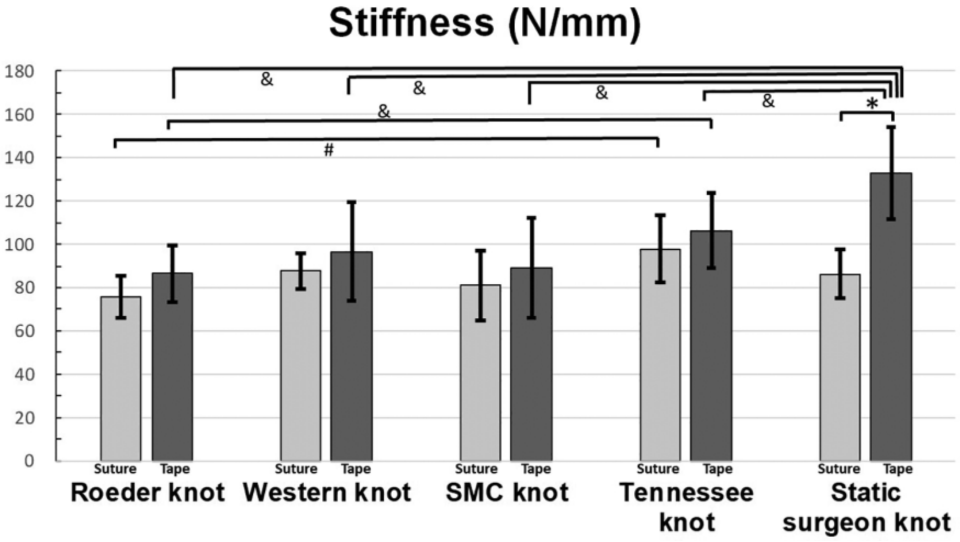

Figure 5. Stiffness of each suture-knot subgroup. Statistically significant differences ($P < .05$): *between the suture and tape groups within the same knot; #between the different knots tied with high-strength round sutures; and &between different knots tied with high-strength tape. SMC, Samsung Medical Center.

round sutures even though the average knot stack height for both tape and round sutures was comparable.[10] Hong et al[7] compared the No. 2 high-strength round suture and 1.3-mm high-strength tape applied for tendon graft fixation using a Krackow configuration and found a greater ultimate failure load in the high-strength tape group. The present study further investigated the biomechanical properties of the round suture and tape in arthroscopic sliding knots and demonstrated greater clinical failure loads in the tape samples than in the round suture samples. These findings are consistent with the reports of prior works[7,10] and support the use of tapes in arthroscopic surgeries.

Although the data from different studies could not be compared directly, the data acquired in the present study were generally consistent with those of the previous studies on this topic. The previous studies[12,16,17] reported that the clinical failure load of a Roeder knot with RHAPs using the round suture ranged from 127 to 157 N, whereas other studies[13,17] reported a clinical failure load in the range of 121 to 134 N for a Western knot with RHAPs using the round suture. In the present study, similar results were found, where the clinical failure loads in the Roeder and Western groups using round sutures were 144.9 N and 134.9 N, respectively. Regarding the SMC knot, Shah et al[17] reported a failure load of 127.2 N using round sutures, whereas the results in the present study demonstrated a clinical failure load of 155.5 N. Regarding the static surgeon's knot, previous studies[12,13] revealed a failure load of approximately 200 N, whereas in the present study, a clinical failure load of 248.2 N was found, which was similar in magnitude.

Elongation of the sutures and knots indicates loosening of the suture loops, possibly affecting the clinical results of repaired constructs.[7] When comparing a tied suture loop among the different knots using the same suture material, loosening of the knot is considered the single contributing factor, assuming that the knot-tying technique was consistent. In the present study, the Roeder, Western, and SMC knots had smaller clinical failure loads than those of the Tennessee knot, especially when the round suture was used. It is possible that the complexity of sliding knots leads to greater opportunities for elongation because there are more suture throws to the knots.

Although seldom discussed, both the yield load and the stiffness of the suture knots are potentially clinically relevant. The yield point has been considered to be the upper limit of elastic deformation, after which permanent deformation begins to occur.[9] Permanent deformation of the suture can possibly cause the formation of a permanent gap between repaired tendon ends or decreases in the tendon-bone contact area after rotator cuff repair. Therefore, a greater yield load value prevents the repaired construct from impaired healing due to permanent structural deformation. The results of the present study showed potential clinical benefits for tapes since the use of tapes in arthroscopic sliding knots resulted in significantly greater yield loads compared with using round sutures. Stiffness describes the ability of an object to resist deformation in response to an applied force.[1] The suture knots with greater levels of stiffness exhibited less elongation when an equal load was given, leading to smaller gap formation in the repaired construct. Since gap formation of the repaired construct has negative clinical effects,[5] using suture knots with greater levels of stiffness, such as the Tennessee knot and static surgeon's knot, could be clinically beneficial.

Limitations

The present study had some limitations. First, the present study was an in vitro biomechanical study. Care should therefore be taken when applying the results in clinical practice. Second, the effects of cyclic loading were not evaluated in the present study. Although cyclic loading tests can be used to simulate postoperative rehabilitation conditions, failure typically occurs at the tissue-suture interface rather than at the knot or suture.[13] According to a biomechanical study,[15] cyclic loading at a low load (10-50 N) for 1000 cycles can lead to significant tendon cut-through. Third, the results of testing under dry conditions may be different from those in a wet environment.[16] In the present study, the suture materials were soaked in normal saline solution for >10 minutes, which was a commonly used procedure in previous studies.[4,8,16,17] Fourth, each knot was tied by 1 surgeon, whose familiarity with certain knots was greater than it was with others. Finally, in the present study, the knots were hand tied without instruments or cannulas. This method was chosen to optimize the quality of the knots and avoid any potential bias from the knot-tying process, which was in accordance with previous studies.[11-13]

CONCLUSION

In this study, it was found that arthroscopic knots tied using 1.3-mm high-strength tape biomechanically outperformed knots tied using No. 2 high-strength round sutures in terms of clinical failure load, yield load, and stiffness.

ACKNOWLEDGMENT

The authors thank the Skeleton Materials and Biocompatibility Core Lab, Research Center of Clinical Medicine, National Cheng Kung University Hospital and National Cheng Kung University Hospital, Tainan (NCKUH-11002049) for their assistance in this project.

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