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# The effect of number of knots per throw, knot technique, and suture type on strength properties of suspensory fixation button surgical procedures

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## ARTICLE INFO

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**Background:** Previous studies of the cortical suspensory button (CSB) implant have analyzed fixation strength as a function of suture type and surgical technique, but knot configuration remains an area of interest. This study investigates 4-strand knot configurations in CSB suspensory fixation, specifically comparing the use of 2 separate knots with a single knot. We hypothesize that using 2 knots on the distal side of the CSB with #2 suture will yield the strongest and stiffest suspensory fixation.

**Methods:** Two types of knot configurations were compared: a single knot with all 4 suture strands versus 2 independent knots with 2 suture strands each (1 knot from inner strands and 1 knot from outer strands). They were tested using #2 or 2-0 suture, and at distal (on top of the button) or proximal (underneath the button) knot positions. Mechanical testing on the Instron measured ultimate failure load, elongation at failure, and stiffness. Statistical analyses (Shapiro-Wilk, unpaired Student's *t*-tests, and Chi-square tests) assessed differences in strength, stiffness, elongation, and failure mode between knot configurations within each CSB construct combination.

**Results:** With #2 suture, 2 knots across the CSB resulted in higher load to failure compared to 1 knot in both proximal (467.00 N vs. 554.66 N, $P = .026$) and distal (395.18 N vs. 526.51 N, $P < .001$) locations. Furthermore, 2 knots provided higher stiffness than 1 knot in both proximal (53.24 N/mm vs. 67.89 N/mm, $P < .001$) and distal (47.08 N/mm vs. 56.73 N/mm, $P = .041$) knot locations. However, using 2-0 suture showed no significant differences in failure load and stiffness regardless of knot location.

**Conclusion:** Using #2 suture and tying 2 independent knots across the CSB increased load to failure and stiffness compared to using only 1 knot regardless of knot position. Thus, if using #2 suture, it is recommended to tie 2 knots to enhance construct strength. However, with 2-0 suture, the number of knots did not impact construct strength. Therefore, if using 2-0 suture, 1 knot can be used to save time. Knot position did not significantly affect the strength or stiffness of the CSB construct, emphasizing the importance of considering knot prominence and surgical approach for determining knot location.

The cortical suspensory button (CSB) is a commonly used orthopedic implant. Suspensory fixation methods have been widely employed in various surgical techniques, including ulnar collateral ligament (UCL) reconstruction, subpectoral biceps tenodesis, distal biceps repair, meniscal root repair, anterior cruciate ligament (ACL) reconstruction, coracoclavicular ligament reconstruction, and syndesmotic stabilization for distal tibiofibular instability,[2,11,14,17,19,25,28,30,34-37] and offer superior outcomes compared to other fixation methods such as aperture fixation and transcondylar pinning.[2,11,17,19,34,35,37] These methods have demonstrated improved biomechanical characteristics, including enhanced strength, stiffness, and minimal elongation of the repair. While many techniques may use a knotless fixation technique via an adjustable-loop retensionable device such as the Arthrex Tightrope (Arthrex Inc., Naples, FL, USA), several technical variations use hand tying of suture over or under the button for fixation. Although it appears to be a simple device, it can be used in several different technical fashions with fixation achieved via a knotless tension device, hand tied surgical knots, or a combination

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of both. Previous studies have primarily focused on analyzing the fixation strength based on factors like suture size, technique, number of strands, number of knots, and type of knot in the absence of a suspensory fixation button.[1,3,5,10,18,29,33] While these investigations have provided valuable insights into optimizing surgical techniques, there is still room for further innovation in achieving an even stronger, stiffer fixation method.

One area of innovation is optimization of the knot configuration. The standard CSB consists of 4 holes which may accommodate varying number of suture strands. If the used surgical technique incorporates 2 separate sutures in the construct, a total of 4 suture ends may exit the CSB. Two common knot configurations have been observed in practice: individually tying strands from the same suture together to create 2 separate knots over the CSB[12,31] and tying all 4 strands into a single knot over the CSB.[9,13] Determination of whether to use a singular knot versus 2 separate knots is commonly based on individual surgeon preference weighing factors such as surgical time, visualization of the button, and experience. However, a biomechanical evaluation to determine objective measures to analyze these differences has not been conducted to date, and it remains unknown which knot configuration yields a stronger and stiffer fixation construct.

An aspect that may influence the ideal knot configuration is the placement of the knot in relation to the CSB and the suture size used. We describe these surgically tied knots as being secured distal, or on top of the button, as compared to proximal, or on the under surface of the button. Most suspensory fixation techniques position the knot on the proximal side of the CSB. This knot position is advantageous because it avoids the potential for an infection nidus implicated in a prominent distal knot.[15,35] Additionally, a proximal knot construct is less likely to fail due to knot slippage as well as reduces the risk for symptomatic prominence of the knot. In constructs with a proximal knot position, the knot is tied on the opposite side of the cortex as the button, as observed in unicortical proximal biceps tenodesis. Alternatively, in cases using bicortical bone tunnels, as seen in bicortical proximal biceps repair and the inlay tension-slide technique in distal biceps repair, the knot is tied on the outside of the opposite cortex as the button.[20,22,23] The authors are not aware of a surgical case in which the button would be tied between the button and the cortex. It should be noted that in some cases, such as in single-incision distal biceps repair and proximal biceps tenodesis, the knot must be tied proximally due to the specific anatomy and surgical approach. Conversely, other techniques position the knot on the distal side of the CSB. This is advantageous for ease of tensioning and subsequent knot tying as seen in all-inside ACL reconstruction,[26] treatment of anterior cruciate joint dislocation and repairing the coracoclavicular ligament,[6,13,17,27] UCL reconstruction,[12,31] and meniscal root repair.[24]

The purpose of this study is to determine whether tying 4 suture strands into 2 separate knots over the CSB yields a stronger, stiffer construct with less elongation at failure than tying 4 strands into 1 knot over the CSB. This objective was tested with 4 combinations of placing the knot on the distal side or proximal side of the CSB and using a 2-0 or #2 suture. We hypothesize that tying separate knots on the distal side of the suspensory fixation device and number 2 suture will yield the strongest and stiffest suspensory fixation.

## Materials and methods

This is a biomechanical study to evaluate various CSB constructs consisting of varying suture size, knot location, and knot configuration with respect to strength, stiffness, elongation at failure, and failure mode. An a priori power analysis was performed based on the variables of ultimate failure load to determine the minimum number of CSB constructs to include in our study. The effect size for the mean ultimate failure load power analysis was based on the standard deviations reported by Borbas et al, a beta of 0.2 and alpha of 0.05.[8] The power analysis indicated a minimum of 8 CSB constructs per group.

**Table I**
CSB constructs.

| Construct | Suture type | Knot location | Number of knots |
|---|---|---|---|
| 1 | #2 | Proximal | 1 |
| 2 | | | 2 |
| 3 | | Distal | 1 |
| 4 | | | 2 |
| 5 | 2-0 | Proximal | 1 |
| 6 | | | 2 |
| 7 | | Distal | 1 |
| 8 | | | 2 |

*CSB*, cortical suspensory button.

### Experimental design

Two types of knot configurations, 1 with a single-knot aggregate and 1 with 2 independent knots, were tested within 4 combinations of CSB constructs. Each construct combination included 1 of 2 high-strength braided suture types, #2 and 2-0 (FiberWire; Arthrex Inc., Naples, FL, USA). These suture types are widely used and are comprised of braided polyester with an ultra-high molecular weight polyethylene core.[4,7] Each combination also included 1 of 2 knot positions, 1 on the distal side and 1 on the proximal side of the CSB, resulting in 8 CSB knot constructs (Table I). The power analysis indicated 8 samples of each of the 8 CSB constructs for a total of 64 samples. The authors' review of the relevant literature estimated that approximately half of CSB surgeries position the knot on the proximal side of the CSB and half position the knot on the distal side of the CSB.

### CSB construct preparation

CSB constructs were created with either 1 knot containing all 4 suture strands or 2 separate knots, each consisting of 2 suture strands from the same suture tied together. The strands of one suture were passed through the inner holes of the button, and the strands of the other suture were passed through the outer holes of the button, which is based on surgeon preference and ease of button fixation. For the 2-knot construct, the inner strands of the same suture were tied together, and the outer strands of the same suture were tied together. Knots were tied either on the distal side (on top of the button) or the proximal side (underneath the button) (Fig. 1).

### Mechanical testing

Mechanical testing was performed using a material testing machine (Instron ElectroPuls E10000; Instron Systems, Norwood, MA, USA). Measurement error of the materials testing machine was certified by the manufacturer to be less than or equal to ±0.01 mm and ±0.3% of the indicated force. Suture loops from the CSB constructs were looped around a dowel that was fixed to the base frame of the material testing machine and oriented such that the loading axis was in line with the direction of the CSB construct longitudinal axis. The CSB with knotted sutures was inserted through a 5-mm diameter hole in a custom fixture that was attached to the end effector of the material test machine (Fig. 2). The mechanical testing protocol was adapted from previously published suture-testing protocols.[8] Each CSB construct was preloaded to 10 N for 20 seconds, and the initial displacement of the

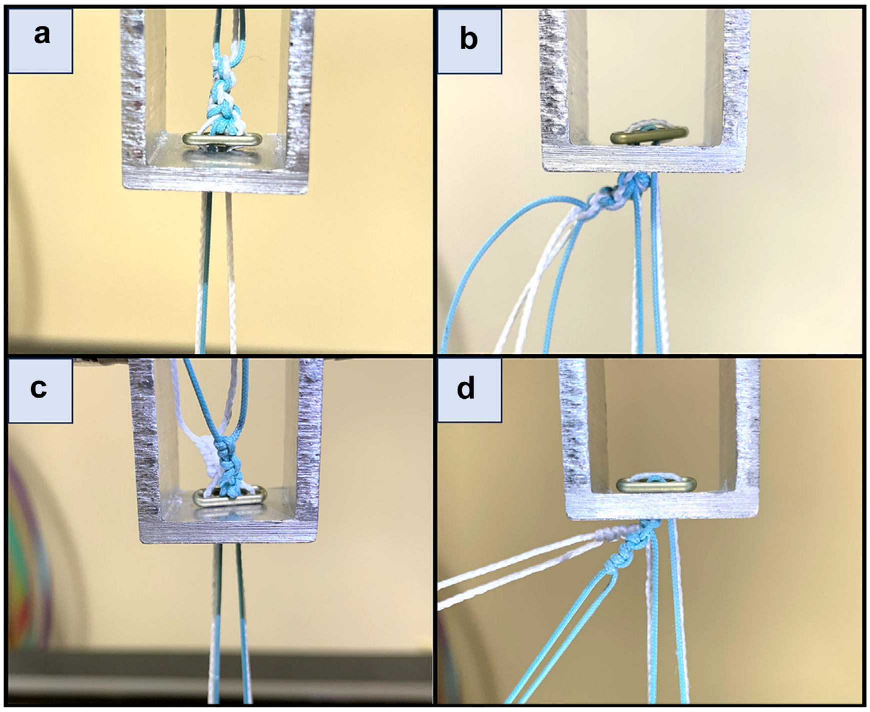

**Figure 1** CSB constructs: (**a**) 1 distal knot; (**b**) 1 proximal knot; (**c**) 2 distal knots; (**d**) 2 proximal knots. *CBS*, cortical suspensory button.

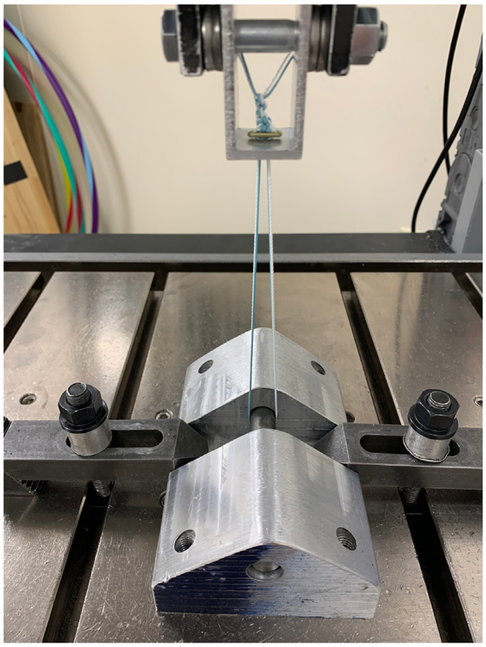

**Figure 2** Mechanical testing setup.

end effector was recorded. The CSB construct underwent tensile displacement at 0.5 mm/s until failure occurred in both suture strands. Ultimate failure load (N) and elongation at failure (mm) were measured from the resulting force-displacement curve. Stiffness (N/mm) was calculated by calculating the slope of the linear portion of this curve. The failure mode of the top (outer) and bottom (inner) strands, on the opposite side, the same side, or at the location of the knot, were recorded.

### *Statistics*

Shapiro-Wilk tests were used to verify normal distribution of ultimate failure load, elongation at failure, and stiffness. Unpaired Student's *t*-tests with post hoc Bonferroni corrections were applied to check for significant differences in these outcomes between knot configurations within each combination of CSB construct. Chi-square test of independence was used to check for significant differences in mode of failure between surgical groups. Statistical significance was defined as $P < .05$.

## Results

In the #2 suture group, 2 knots across the CSB resulted in higher load to failure compared to a single knot for both proximal (467.00 N vs. 554.66 N) and distal (395.18 N vs. 526.51 N) knot locations. However, the number of knots tied in the 2-0 suture group did not significantly affect failure load regardless of knot location (Fig. 3). In the #2 suture group, 2 knots also provided greater stiffness compared to 1 knot for both proximal (53.24 N/mm vs. 67.89 N/mm) and distal (47.08 N/mm vs. 56.73 N/mm) knot locations. However, the number of knots tied in the 2-0 suture group did not significantly affect stiffness regardless of proximal or distal knot location (Fig. 4). The 1-knot configuration with a proximal knot location in the #2 suture group had the longest elongation at failure of 11.90 mm, but this was not significantly greater than any other configuration. Conversely, the 2-knot configuration with a distal knot location in the 2-0 suture group had the shortest elongation at failure of 5.23 mm, but this was not significantly less than any other configuration (Fig. 5). The failure mode of the top strand was widely variable with the strand failing at the opposite side, the same side, or at the location of the knot. On the other hand, the failure mode of the bottom strand was found to be almost always at the location of the knot (Fig. 6).

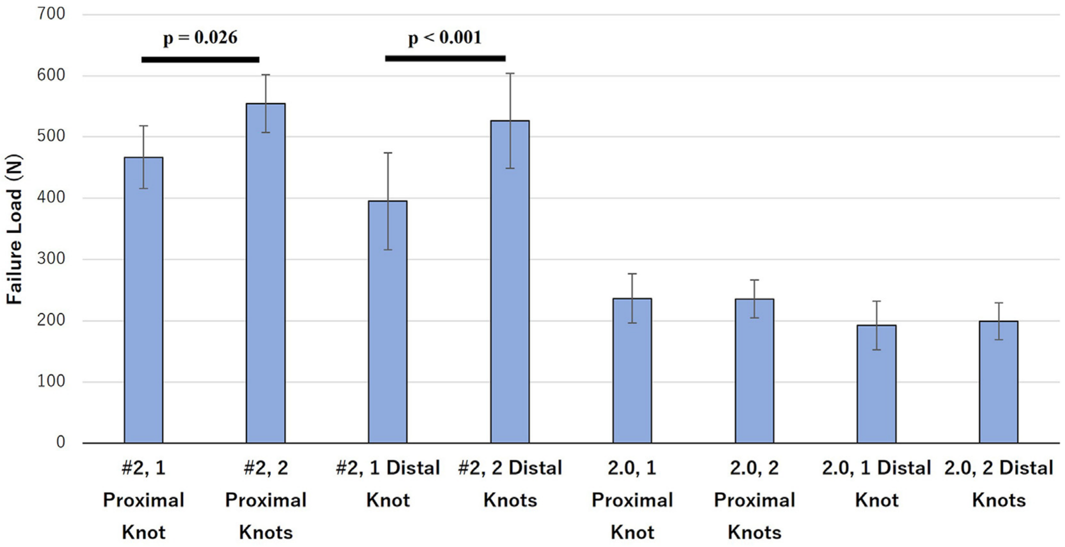

**Figure 3** Failure load of CSB constructs with 1-knot or 2-knot configurations, proximal or distal knot location, and with #2 or 2-0 suture. Comparisons were made between 1-knot and 2-knot configurations within each knot location and suture type. *CBS*, cortical suspensory button.

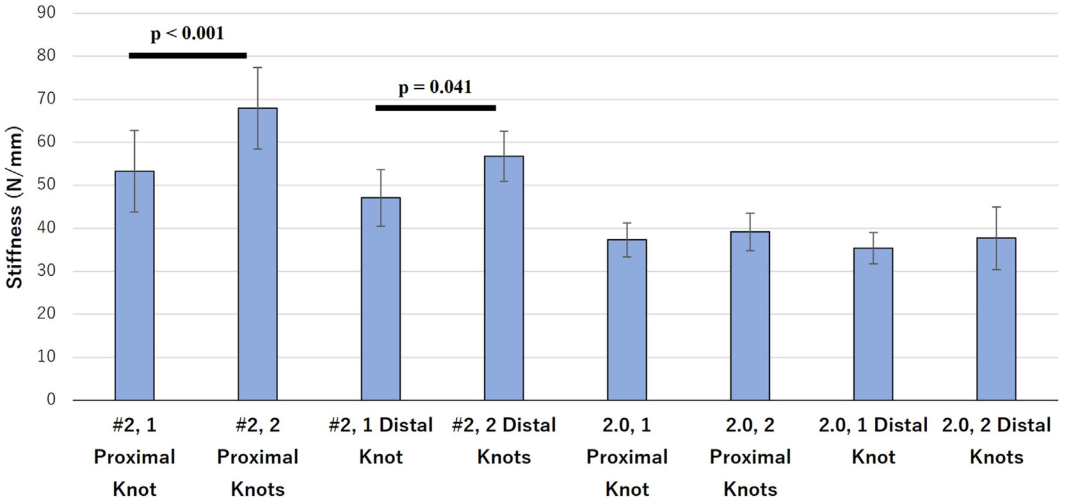

**Figure 4** Stiffness of CSB constructs with 1-knot or 2-knot configurations, proximal or distal knot location, and with #2 or 2-0 suture. Comparisons were made between 1-knot and 2-knot configurations within each knot location and suture type. *CBS*, cortical suspensory button.

## Discussion

In constructs with #2 suture, 2 knots across the CSB provided a higher load to failure than only 1 knot in both a proximal and distal knot configuration. In constructs with #2 suture, 2 knots across the CSB provided a higher stiffness than only 1 knot in both a proximal and distal knot configuration. However, there were no differences in failure load and stiffness with respect to the number of knots tied in 2-0 suture regardless of proximal or distal knot configuration.

These results are supported by those reported in the literature. Jin et al compared biomechanical properties of 3 different suspensory fixation devices used in ACL reconstruction.[16] They found that the mean load to failure for a knotted tightrope was 868.1 N, which is more than our value of 526.5 N. The tightrope construct is knotless, so tying over the distal aspect of the button was hypothesized to provide additional strength. However, the authors found that tying knots over the button did not have a statistically significant effect on failure load but did reduce total displacement of the construct when subjected to an applied load. This study did not examine the effect of number of knots tied, and possibly had a higher load to failure than in our study because the ultimate strength of the tightrope is not dependent solely on the knot configuration. Vopat et al describe a biomechanical comparison of UCL reconstruction using a CSB in a single tunnel proximal suspensory fixation versus a modified docking technique.[31] The authors describe hand tying 2 separate knots on the distal aspect of the button. Biomechanical analysis revealed an ultimate failure torque of the proximal single tunnel technique of 30.9 Nm, which was greater than previously reported in the literature. Their explanation for this is that their study tied 2 separate knots over the CSB instead of 1 knot. This agrees with our findings that 2 knots demonstrate higher load to failure than 1 knot in #2 suture.

The ultimate failure load of the knot configurations tested in this study is likely related to the stress concentrations in the suture where the suture enters the knot. Stress concentrations within the sutures of the knots are affected by the radius of curvature of the

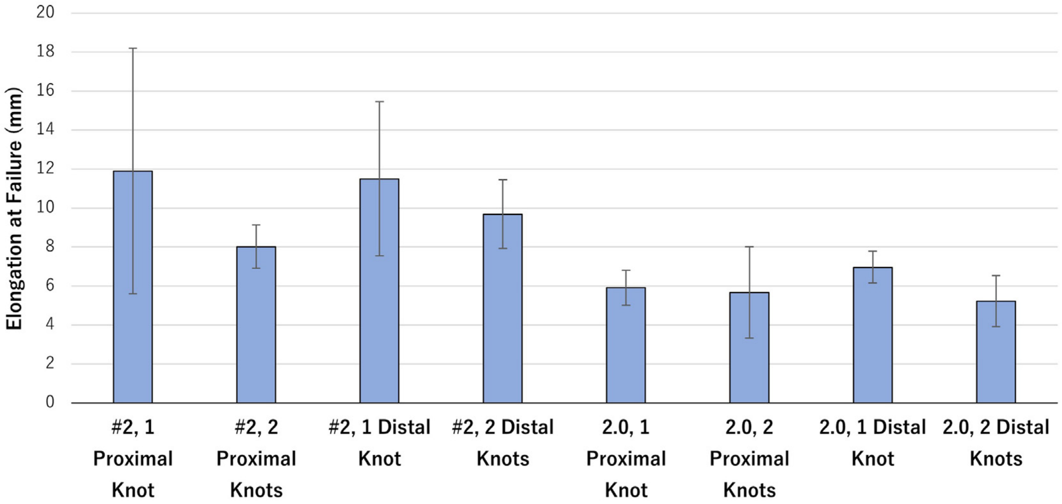

**Figure 5** Elongation at failure of CSB constructs with 1-knot or 2-knot configurations, proximal or distal knot location, and with #2 or 2-0 suture. Comparisons were made between 1-knot and 2-knot configurations within each knot location and suture type. *CBS*, cortical suspensory button.

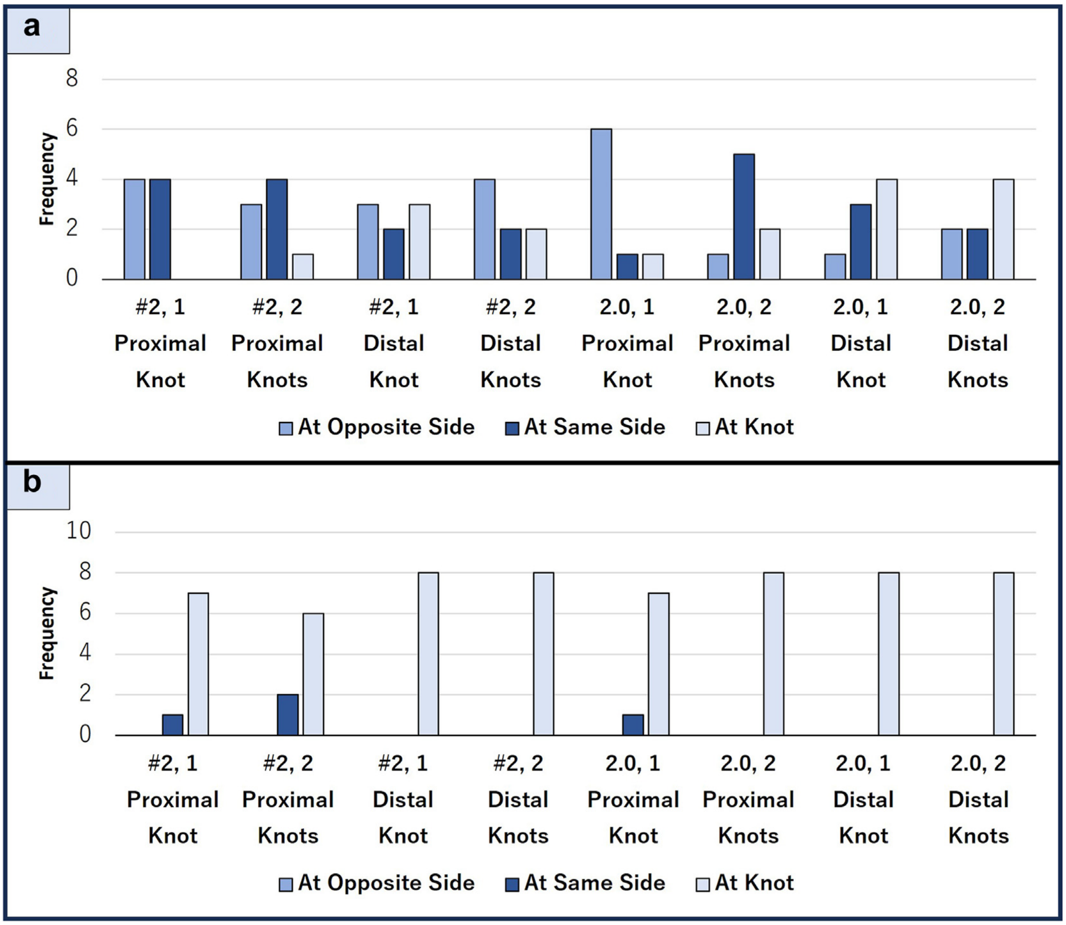

**Figure 6** (**a**) Failure mode of top strand and (**b**) bottom strand in the CSB construct, at the opposite side, same side, or at the location of the knot. *CBS*, cortical suspensory button.

suture as it enters the knot and the amount of compression that the strand experiences from the knot itself, a factor that is related to the tension that is applied to the suture.[21] This is consistent with our findings that the most common mode of failure was at the knot. The authors believe that the thickness of the #2 suture may reduce the stress concentration within the strand due to the strand radius of curvature as it enters knot. Stress concentrations due to strand compression are higher in the 1-knot versus the 2-knot configuration because the strands are in contact in the 1-knot configuration such that strand compression in 1 strand is transmitted to the neighboring strand and vice versa, which elevates the stress concentrations in both strands. In the 2-knot configuration, contact does not occur between strands, so strand compression is not affected by the other strand in the configuration, and the strand experiences a lower stress concentration as a result. Thus, the elevated stress concentration in the 1-knot configuration leads to a weaker, less stiff construct than the 2-knot construct. The reason why this difference is not detected in the constructs with the 2-0 suture is that the suture thickness is smaller than the #2 suture such that the radius of curvature of the 2-0 suture as it enters the knot is lower than the #2 suture. It is important to note that the construction of the #2 and 2-0 suture used in the study is the same.[4,32] However, the 2-0 suture's smaller radius of curvature increases the stress concentration within the suture such that the suture fails at the knot regardless of the amount of relative compression in the suture due to the 1-knot versus 2-knot construct.

This study was not without limitations. First, this study incorporated in vitro experimentation with supraphysiological loads applied to the suture-CSB constructs. Clinically, there are other causes for fixation failure, including suture pullout from soft tissue as well as bone fracture, that the authors did not test for. It is important to note that, when dealing with smaller tendons, ligaments, or grafts, the need for 2 sutures is less common. Thus, there are many procedures that involve less than 4 limbs of suture, rendering the findings of this study inapplicable in such cases. Furthermore, the study tested only the most common knot configurations and positions used in clinical settings, although other combinations may exist that were not tested, such as placing the knot between the undersurface of the button and the cortex or placing suture limbs of the same suture through adjacent holes rather than the inner and outer holes. Additionally, the testing condition used fixed loops of suture with knots, whereas in clinical settings, this construct may vary from whipstitched grafts, varying CSB sizes and suture configurations, varying number of knot throws, among other conditions that were not tested.

## Conclusion

When performing a surgery that uses a construct consisting of 2 sutures and a CSB, it is advantageous to tie 2 separate knots if using #2 suture. When using 2-0 suture, the number of knots does not impact construct strength, so tying all 4 strands into 1 knot can be performed to save time. The strength or stiffness of the CSB construct is not affected by proximal or distal knot placement, so consideration of knot prominence as well as surgical approach should dictate the knot location.

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