Remplissage Using Interconnected Knotless Anchors: Superior Biomechanical Properties to a Knotted Technique?

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**Purpose:** To evaluate the biomechanical fixation strength and gap formation of 2 different remplissage fixation methods (double pulley knotted construct and interconnected knotless repair construct) in cadaver specimens. **Methods:** Seven matched pairs of human cadaveric shoulders were used for testing (mean age, 56 ± 10 years). A shoulder from each matched pair was randomly selected to receive a Hill-Sachs remplissage using either a knotted (No. 2 FiberWire double pulley with 3.0-mm SutureTak anchors) or knotless (coreless No. 2 FiberWire interconnected between 3.9-mm knotless CorkScrew anchors) double mattress construct. The tendon was cycled between 10 and 100 N at 1 Hz for 100 cycles, followed by a single-cycle pull to failure at 33 mm/s. Cyclic displacement, load to clinical failure (5 mm), yield load, and mode of failure were recorded. **Results:** Neither construct demonstrated clinical failure under cyclic loading. Load to clinical failure was higher for the knotless repair than that of the knotted repair (788 ± 162 N vs 488 ± 227 N; P = .003). The yield load was higher for the knotless repair than that of the knotted repair (1,080 ± 298 N vs 591 ± 265 N; P = .008). The most common failure mode for the knotted repair was knot failure or tendon tearing, whereas the failure mode for the knotless repair was by anchor pull-out or tendon tear with no failures occurring via the interconnected suture construct mechanism. **Conclusions:** In this biomechanical study comparing cyclic and ultimate loading for 2 double mattress remplissage repairs, the construct using interconnected, knotless sutures outperformed the knotted construct. No failure of the interconnected suture construct mechanism by slippage or breakage was observed in the knotless group. **Clinical Relevance:** The use of the interconnected knotless suture technique might improve the biomechanical strength of arthroscopic remplissage repairs in treating shoulder instability.

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The procedure of arthroscopic remplissage has been used successfully to improve shoulder stability in cases where a Hill-Sachs lesion of the humerus engages\(^1\) the glenoid or is biomechanically at risk for engagement (“off-track” lesion).\(^2\) Insetting the posterior rotator cuff into a significant Hill-Sachs lesion represents a nonanatomic reconstruction of the shoulder, but is supported by both clinical\(^3\) and biomechanical\(^4\) studies that demonstrate the effectiveness of this procedure. Successful outcomes of arthroscopic procedures such as remplissage require secure, primary fixation at the site of tendon-to-bone interface to allow biologic healing to occur. Although knot tying is an essential skill for proficiency in arthroscopic surgery,\(^5\)\(^-\)\(^9\) knots remain a potential site of failure\(^6\)\(^,\)\(^9\)\(^,\)\(^10\) of knotted repair constructs.\(^11\) Evidence has shown that considerable variation exists in knot tying consistency and knot strength among surgeons.\(^6\)

Knotless suture anchors of varying design have been an important advance in arthroscopic shoulder surgery. Knotless anchors have the theoretical advantages of decreased operative time, simplicity of suture management, and the elimination of knots as a source of potential failure sites.\(^5\)\(^-\)\(^9\) The strength of these anchors is related to the design of the anchor itself and the method of suture engagement.\(^5\)\(^-\)\(^9\)\(^,\)\(^10\)\(^-\)\(^12\)
of cartilage wear or postoperative pain. Additionally, one knotless anchor design (Knotless SutureTak and Knotless CorkScrew; Arthrex, Naples, FL) has an internal splice locking mechanism in the anchor body (Fig 1) that has the purported advantages of being tensionable and self-cinching (self-reinforcing).

The purpose of this study was to evaluate the biomechanical fixation strength and gap formation of 2 different remplissage fixation methods (double pulley knotted construct and interconnected knotless repair construct) in cadaver specimens. Our hypothesis is that, in a cyclic loading and load-to-failure biomechanical study, the interconnected knotless construct will be equivalent to the knotted construct comparing load at 5 mm of displacement and yield load.

Methods

Local institutional review board approval was granted for this biomechanical study. Seven matched pairs of fresh frozen cadaveric shoulders (all male specimens) with a mean age of 56 ± 10 years underwent simulated knotted and knotless Hill-Sachs remplissage followed by biomechanical testing. The sample size was determined arbitrarily, but was in keeping with similar previous studies and the reasonable constraints of time, availability, and cost of specimens. The specimens were thawed overnight before preparation. Each shoulder was dissected such that only the humerus with the rotator cuff tendons and capsule remained. The distal humeral shaft was potted in PVC pipe using fiberglass epoxy resin. Specimens were prepared in a pairwise manner with care to ensure even allocation of repairs between left and right specimens. Specimen preparation, testing, and assessment was done by the authors, who all are fellowship trained in shoulder surgery and are experienced in conducting biomechanical studies.

Simulated Hill-Sachs Remplissage

Because the specimens were intact with regard to the humeral head, the remplissage was simulated by fixing the rotator cuff and capsule onto the intact cartilage. Creation of an experimental Hill-Sachs lesion was avoided to maintain the integrity of the subchondral bone with the goal of minimizing anchor failure such that the mechanical properties of the suture constructs (rather than anchor properties) could be compared. The location of the remplissage was centered over the infraspinatus tendon by calculating half the distance between the suprainfraspinatus raphe and the superior aspect of the teres minor insertion (Fig 2). The remplissage was thus centered at approximately the 2 o’clock (right shoulder) or 10 o’clock (left shoulder) position (Fig 2). The 2 suture anchors were placed 15 mm apart and 15 mm onto the humeral head articular cartilage measured from the infraspinatus capsular insertion (Fig 2), thus, simulating a small to moderate sized Hill-Sachs lesion by width. The anchors were placed and retrieved through the cuff for all specimens.

Knotted Group

In the knotted group, the PEEK (polyether ether ketone) 3.0-mm SutureTak anchors were placed as above leaving 1 strand of No. 2 FiberWire (Arthrex) in each anchor. The sutures were tied as a double-pulley mattress after being retrieved through the rotator cuff just lateral to the musculotendinous junction using a Penetrator suture passer (Arthrex; Fig 1B) with 1 pass for each suture. The first knot of the double pulley was tied by hand using a 6 throw surgeon’s knot. The second knot was tied using a Surgeon’s 6th Finger knot pusher (Arthrex) to simulate an arthroscopic repair (Fig 3A).

Knotless Group

In the knotless group, the 2 PEEK 3.9-mm Knotless CorkScrew anchors were placed as above with respect to location on the humeral head. The sutures were passed through the infraspinatus tendon in the same manner as in the knotted group. The remplissage construct in the knotless group was created by threading the coreless No. 2 FiberWire repair suture from each anchor into the suture splice locking mechanism of the other anchor. The threaded repair sutures were then tensioned sequentially such that 2 suture limbs compressed tendon to bone (Fig 3B).
Biomechanical Testing

The potted humeral shaft was positioned in a custom-made fixture that was mounted vertically on the table of a servohydraulic materials testing machine (MTS Systems, Minneapolis, MN). Using an adjustable angle fixture, the humerus specimen was fixed at an angle and position of rotation such that the line of force on the infraspinatus tendon simulated that which would occur in the apprehension position of the shoulder (60°/14° of abduction in the coronal plane and approximately 30° posterior to the scapular plane) but midrange rotation (60°). The infraspinatus musculotendinous unit (Fig 4) was then fixed in the cross-head of the machine using a cryo clamp, and visual verification was done to ensure that the vector of pull was normal to the repair construct (Fig 4).

The tendon was cycled between 10 and 100 N at 1 Hz for 100 cycles, followed by a single-cycle pull to failure at 33 mm/s. Force-displacement curves were generated for each specimen. Clinical failure was defined as

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**Fig 2.** Left shoulder specimen during preparation. Two suture anchors (PEEK SutureTak, 3.0 mm) were inserted 15 mm apart (A) centered at about the 10 o’clock position of the humerus (left shoulder). The sutures were passed just lateral to the musculotendinous junction using a suture retriever (B). The remplissage was centered over the infraspinatus tendon as determined by the borders of the suprainfraspinatus raphe and the characteristic upper border muscle fibers of the teres minor.

**Fig 3.** Left shoulder specimen during preparation. In both knotted (A) and knotless (B) groups, a double mattress suture construct was used to create a simulated remplissage construct. In the knotted group, No. 2 FiberWire, an ultra-high-molecular-weight polyethylene (UHMWPE) core strand jacketed with braided polyester-UHMWPE, was secured with 2 surgeon’s knots (6 throws). In the knotless group, the suture was No. 2 FiberWire coreless (core strand removed).
5 mm of displacement. For each specimen, load at clinical failure\textsuperscript{7,13,16} and yield load (yield point defined as sudden drop in tensile forces signified by change in slope of force–displacement curve) were recorded.

A digital video camera (Handycam, SONY, Tokyo, Japan) recorded the testing procedure to document the mode of failure at the yield point. The mode of failure was reported for each specimen.

Statistical Analysis

Results are reported as mean ± standard deviation. Statistical analysis for yield load and load at 5 mm of displacement was done with (SigmaPlot 11 software; Systat Software, San Jose, CA). A paired \( t \) test was used to for statistical comparison between the 2 groups. Statistical significance was set at \( P < .05 \). No a priori power analysis was performed because the sample size was constrained by available resources, as stated.

Results

No clinical failure (more than 5 mm of displacement) was observed in any specimen after the first 100 cycles. The mean loading force to create a 5-mm displacement in the knotless group (788 ± 162 N) was significantly higher than that in the knotted group (488 ± 227 N; \( P = .003 \)). The load to failure (yield load) for the knotless group (1,080 ± 298 N) was higher than that for the knotted group (591 ± 265 N; \( P = .008 \)). Displacement at the yield point in the knotless group (6.6 ± 1.3 mm) was not significantly different from that in the knotted group (6.0 ± 1.7 mm) (Table 1).

In the knotted group, there were no failures involving pullout of the anchor (Table 2). In the knotted group, failure occurred via the suture (breakage or knot loosening) or tendon tearing in all cases. In the knotless group, failure occurred by pullout of the anchor in 4 cases and tendon tear in 3 cases without any observed failure of the suture construct.

Discussion

In the current study, the biomechanical testing of knotless versus knotted double mattress remplissage suture constructs confirmed the hypothesis that the specific knotless method using anchors with an internal splice locking mechanism\textsuperscript{13} had at least equivalent strength to the knotted method when tested under cyclic loading and load to failure. In fact, under load to failure testing, the knotless construct had far better strength than the knotted construct.

Previous studies have demonstrated mixed results regarding the biomechanical superiority of repairs

\begin{table}[h]
\centering
\begin{tabular}{lccc}
\hline
 & Knotted Group & Knotless Group & \( P \) Value \\
\hline
Load to Clinical Failure, n & 488 ± 227 & 788 ± 162 & .003 \\
Yield Load, n & 591 ± 265 & 1080 ± 298 & .008 \\
Displacement at Yield Load, mm & 6.0 ± 1.7 & 6.6 ± 1.3 & .5 \\
\hline
\end{tabular}
\caption{Cyclic Loading and Load-to-Failure Testing of Knotted and Knotless Remplissage Constructs}
\end{table}

*5 mm of displacement.
Table 2. Observed Modes of Failure During Biomechanical Testing of Knotted and Knotless Remplissage Constructs

<table>
<thead>
<tr>
<th></th>
<th>Knotted Group</th>
<th>Knotless Group</th>
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<tbody>
<tr>
<td>Tendon Tear</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Suture Breakage</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>Suture Loosening</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>Anchor Pull-out</td>
<td>0</td>
<td>4</td>
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performed using knotless anchors. Burkhart and Athanasiou previously outlined and validated the mechanisms for improved security of 1 knotless fixation method (twist-lock) over a knotted construct. Conversely, Uggen et al. noted suture slippage around a similar style of knotless anchor as the mode of failure in biomechanical testing of SLAP repairs in 5 of 6 cases (83%). In the current study, the specific knotless anchor mechanism is a novel, self-reinforcing suture locking system similar to a “Chinese finger trap,” in which the system grips more tightly as a tensile longitudinal force increases against the suture loop. Self-reinforcement is very desirable and this particular characteristic of the knotless anchor design may have been responsible for the results seen in this study.

In the current study, the mechanical integrity of the suture fixation in the knotless group was excellent, as demonstrated by (1) the superior load to failure and (2) the fact that the failure mode for the knotless group was usually tendon tear or anchor pullout rather than suture breakage or slippage. In addition to the self-reinforcing nature of the knotless anchors (increased frictional forces against suture slippage as the load increases tightens), for the knotless construct to fail by suture slippage or breakage, each suture would have to fail because they are each fixed to the opposite anchor independently. In the knotted construct, only 1 knot has to slip or break to result in failure of both sutures because they are tied together. Furthermore, this type of biomechanical experiment provides the best case scenario for knot integrity because these knots were tied under close scrutiny under controlled laboratory conditions.

Limitations

This study does have limitations. The very specific design mechanism of the knotless anchor (internal suture splice mechanism in the anchor body) is unique to the manufacturer (Arthrex), and these results should not be assumed to extrapolate to other anchors of the same general kind (“knotless”). Some variables besides the suture fixation method (knots vs knotless), were not able to be held constant between groups, primarily due to anchor design. In the knotted group, a 3.0-mm “push-in” anchor was used, whereas the knotless group had a 3.9-mm threaded anchor. Additionally, the suture itself was different (No. 2 FiberWire vs coreless No. 2 FiberWire), also owing to differences in anchor design. This limitation of anchor differences did not seem to be experimentally relevant, because the smaller anchor did not fail in any case by anchor pull-out. Additionally, the suture material differences did not seem to be experimentally relevant, because the coreless suture did not fail in any case by breakage or loosening. The bone density of the cadaver specimens was unknown, which could have potentially affected the results had different modes of failure been observed. Last, this study has the weakness inherent in a biomechanical study performed on cadaveric specimens with the variability in tissue quality between specimens.

Conclusions

In this biomechanical study comparing cyclic and ultimate loading for 2 double mattress remplissage repairs, the construct using interconnected, knotless sutures outperformed the knotted construct. No failure of the interconnected suture construct mechanism by slippage or breakage was observed in the knotless group.

Acknowledgments

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References


