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ORIGINAL ARTICLE

The Interlocking Modification of the Cross Locked Cruciate Tendon Repair (Modified Adelaide Repair): A Static and Dynamic Biomechanical Assessment

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Abstract The 4-strand cross-locked cruciate flexor tendon repair technique (Adelaide technique) has been shown to have comparably high resistance to gap formation and ultimate tensile strength. This study aimed to determine whether an interlocking modification to the Adelaide repair would impart improved biomechanical characteristics. Twenty four sheep flexor tendons were harvested, transected and repaired using either standard or modified Adelaide techniques. Repaired tendons were cyclically loaded. Gap formation and ultimate tensile strength were measured. Additionally, suture exposure on the tendon surface was determined. There was a statistically significant increase in resistance to gap formation in the early phase of cyclic loading within the modified Adelaide group. In the later stages of testing no significant difference could be noted. The average final load to failure in the modified group was higher than the standard group but this did not achieve statistical significance. Interlocking suture techniques in four strand tendon repair constructs can improve gapping behavior in the early phase of cyclic loading.

Keywords Flexor tendon · Tendon repair · Locking stitch · Gap formation

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Introduction

It is established that early mobilization of reconstructed flexor tendon injuries has significantly improved functional outcomes [1, 2]. This has been enabled through improved rehabilitation protocols and also through the evolution in repair techniques. Previous work has indicated that two-strand core repairs may not be strong enough to withstand the higher loads imposed by early active mobilization [3]. This has led to the development of numerous 4 and 6 strand core repair techniques. Increasing the number of core strands leads to increased load to failure [4, 5] and improved resistance to gap formation [6]. However, many of these multi-strand techniques have been criticized due to their bulk, complexity, or required tissue handling.

The 4 strand, cross-locked cruciate repair (Adelaide repair) [7–11] (Fig. 1) is an adaptation of the 6 strand Savage tendon repair technique [12]. It can also be described as a cross locked modification of the 4 strand cruciate repair [13]. The Adelaide repair seems to demonstrate a good compromise between, strength, simplicity and bulk without excessive tissue handling [14–18]. Previous work has demonstrated that the properties of the cross locks are integral to the overall biomechanical behavior of the repair [19]. We hypothesize that a simple interlocking modification to the cross locks of the Adelaide repair can increase final pull to failure loads while also increasing resistance to gapping. This study aims to compare the standard Adelaide repair to a modified, interlocking Adelaide repair using both cyclic and static testing protocols.

Materials and Methods

Twenty four deep flexor tendons were harvested from the fore limbs of sheep of a similar age (18–24 months). Twelve fore limbs were used in total, each limb containing two deep digital

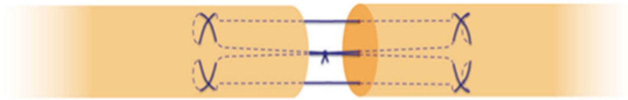


Fig. 1 Four strand cross locked cruciate Adelaide repair technique

flexor tendons. One tendon from each limb was randomly allocated to either the standard Adelaide or modified (interlocking) Adelaide group. As previously described, all tendons were sharply transected at a standardized point 5 mm distal to the A1 pulley at a zone equivalent to zone 2 [19].

Twelve tendons in the standard group underwent Adelaide repairs performed according to previously described techniques (Fig. 1) [8, 19]. Tendons were repaired on the volar aspect using 3–0 braided polyester suture (Ticron; Tyco Healthcare, Norwalk, CT) for the core strands. Suture purchase was kept constant at l0mm. The cross-locks were kept at 4 mm in both transverse and longitudinal dimensions and placed in the volar half of the tendon circumference (9 to 3 o'clock, 12 o'clock being the most volar point). Care was taken to keep the repair technique standardized and a metric ruler was used for this aid. A single four throw (1+1+1+1) square knot was tied between tendon ends. Repairs were slightly tensioned to achieve a shortening of the encompassed tendon segment by approximately 10 % before testing.

The remaining twelve tendons were repaired using an interlocking modification which involved interlocking of the distal angles of the cross locks through each other (Figs. 2 and 3). Cross lock size (4 mm), suture purchase (10 mm) and depth was again kept constant. Repairs were all carried out using 3.2× loupe magnification. After repair, tendons were immediately wrapped loosely in cotton gauze swabs moistened with phosphate buffered saline and sealed in airtight containers before being stored in a freezer at −20 degrees Celsius. They were then allowed to fully defrost at room temperature for 8 h before mechanical testing [20].

Mechanical Testing

Dynamic and static testing were performed at room temperature (22–25 degrees Celsius) using a mechanical testing device (MTS 858 Mini Bionix II, Eden Prairie, MN USA). Care was taken to avoid tendon dehydration by intermittent irrigation with phosphate buffered saline solution. Repaired tendons were mounted in hydraulic clamps, with the clamps placed 40 mm apart, equidistant from the repair site. Tendons were then subjected to cyclic loading.

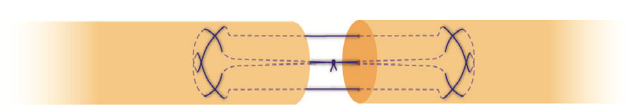


Fig. 2 Modified (interlocking) Adelaide repair technique

Fig. 3 Transected sheep tendon repaired using a modified Adelaide core repair

Each tendon was loaded in tension from 3 N to 30 N and back to 3 N for 250 cycles at a rate of 1 Hz. These loads simulate an active mobilization protocol and are based on previous studies [21–23]. Testing was paused at 10, 20, 30, 40, 50, 100, 150, 200 and 250 cycles and the repair site gap measured at 3 N trough load. Gap measurement was made with the aid of a pre-mounted digital camera (Fig. 4a, b and c). A photograph of the repair site was taken with a digital caliper (Mitutoyo CD-6" CS Absolute Digimatic. Tokyo, Japan) fixed at 10 mm placed adjacent to the repair, serving a reference point for assessment of gap formation. Gap measurements were then made in each taken picture at eight locations across the repair site using Image analysis software (Image J 1.410, National Institutes of Health, Bethesda, MD). Mean gap (mm) was then determined by averaging the eight measured lengths across the repair site (Fig. 4c). Accordingly the suture exposure on the tendon surface was measured. Again using image analyzing software and basing measurements on the known length of the 10 mm caliper the overall length of exposed suture material of each repair at each cycle point was identified (Fig. 5).

Following the cyclic testing, a static pull-to failure was carried out. Each tendon was distracted to failure at a rate of 20 mm/min and the load at failure measured. Data regarding load, displacement and time was recorded at a sampling rate of 100 Hz. Data gathered was used to generate load displacement curves for each tendon. Data were analyzed with SPSS v17.0 (SPSS Inc., Chicago, IL). Two-sample t-test was used to compare the different endpoints between groups. $P<0.05$ was considered statistically significant.

Results

Gap Formation

The average gap formation of both groups after 250 cycles was not statistically different (3.95 mm in the standard Adelaide group, 3.80 mm in the modified group). The rate of gap formation was highest over the first 50 cycles. However, in the early phase of cyclic loading (up to 10 cycles) gap formation was significantly lower ($p=0.02$) in the modified Adelaide

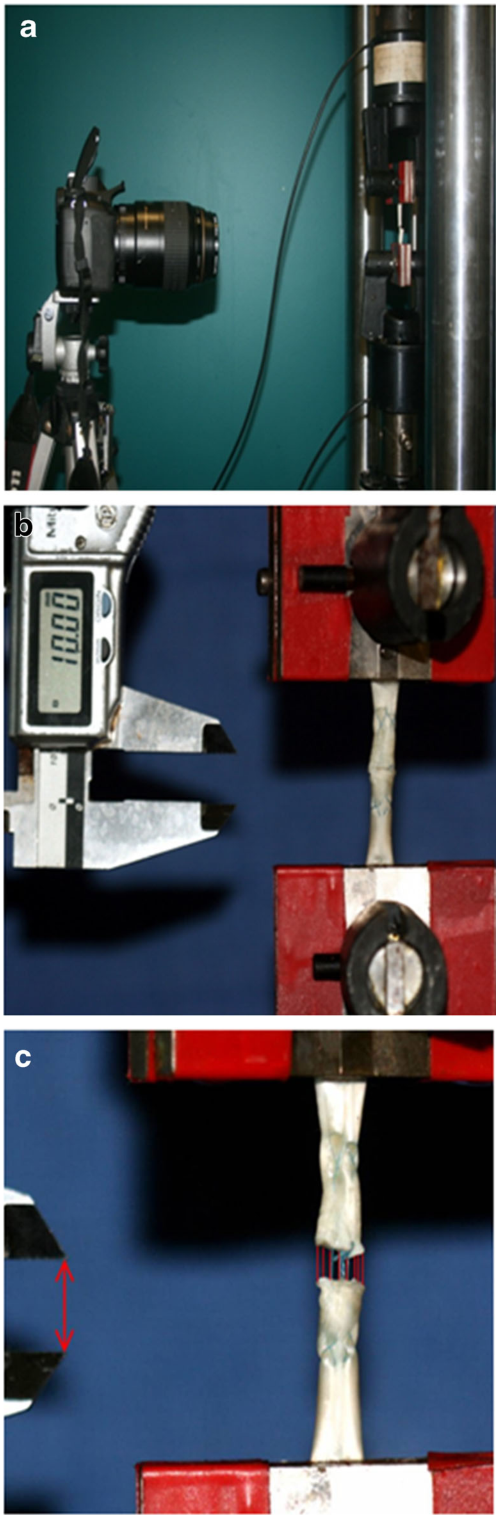


Fig. 4 (**a**–**c**): Mechanical testing set-up: A digital photograph (**a**) was taken with a caliper fixed at 10 mm adjacent to the repair site (**b**). Mean gap in mm was measured with Image-J software averaging eight measured lengths across the repair site for each tendon at each testing point (**c**)

group (0.72 mm +/− 0.6) compared with the standard Adelaide group (1.56 mm +/− 0.49) (Figs. 6 and 7).

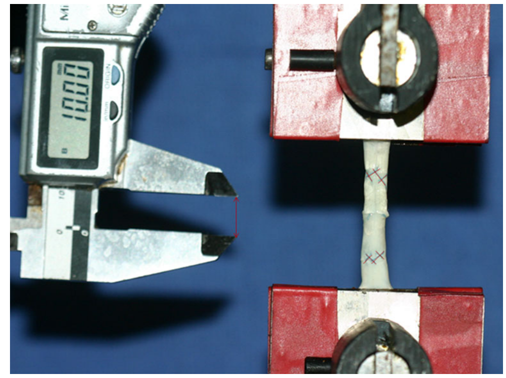


Fig. 5 Measurement of exposed suture length on tendon surface

Final Load to Failure

The average final load to failure in the standard Adelaide group was 48.6 N (+/− 5.94) compared to 51.9 N (+/− 3.0) in the modified Adelaide group (Fig. 8). Our results showed that by interlocking the distal locking components in an Adelaide repair, the final load capacity increased by 6.83 %. Although we observed this trend towards increased load to failure in the modified Adelaide group, this did not achieve statistical significance (p=0.13).

Mechanism of Failure

Static pull to failure testing caused complete repair rupture and failure at the knot in all cases regardless of repair technique. No suture pullout was observed in either group.

Suture Exposure on Tendon Surface

There was no significant difference in measured lengths of suture exposure on tendon surface between groups. Average total exposed suture length in Adelaide group was 29.78 mm (+/− 2.0) versus 31.70 mm (+/− 2.1) in modified Adelaide group (p>0.05) (Fig. 9).

Discussion

The ideal technique for tendon repair should be easily reproducible, possess high tensile strength, high resistance to gap formation and ultimately allow for early active mobilization [24]. Flexor tendon repair techniques have evolved and undergone constant modification in a bid to achieve the desired balance between strength and simplicity. Six core strand techniques impart strength but increased bulk of the repair and increased tissue handling are potentially detrimental to the tendon [25]. Two core strand techniques encounter these problems to a lesser degree but do not possess the desired durability

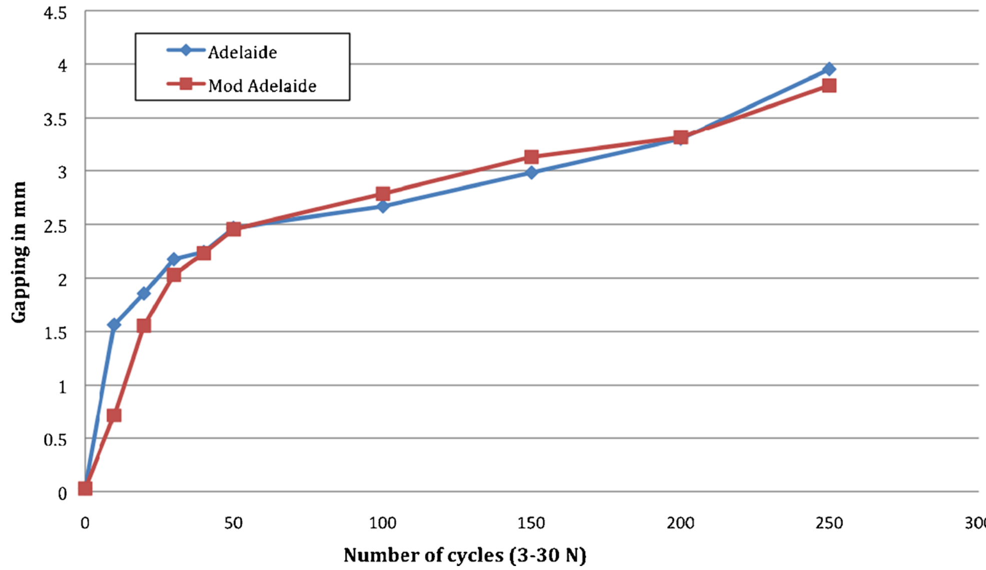


Fig. 6 Final load of failure of repair techniques

under loads imparted by active mobilization regimes [26]. Four core strand repairs seem to achieve this balance more successfully. In particular, previous studies have demonstrated the favorable biomechanical characteristics of the cross-locked cruciate 4 strand technique [15–18, 24] and indicate that this technique may offer a good compromise between the desirable and undesirable aspects of tendon repairs.

During the evolution of 4 strand repairs, several authors have described differences in the biomechanical properties of grasping loops and locking loops [17, 27–31]. These differ from the cross locks seen in the Adelaide repair and the modification we describe. Croog et al. [17] and Barrie et al. [14, 15] demonstrated that within the context of 4 strand repairs, the use of locking cross stitches confers significant benefits over repairs using looped techniques. They demonstrated that gap force and ultimate tensile strength were both improved by using a cross lock. The benefit of the cross locks is that they have less propensity to deform under load than looped techniques [15, 16, 19, 28–32]. Consequently, the tendon repair is less prone to gap formation. Previous work [19] examined the influence of altering the size of the locking cross stitch in the Adelaide repair. In contrast to simple loop locks, increasing the size of the cross locks can offer improved resistance to gap formation. Therefore subtle differences in the configuration of cross locks

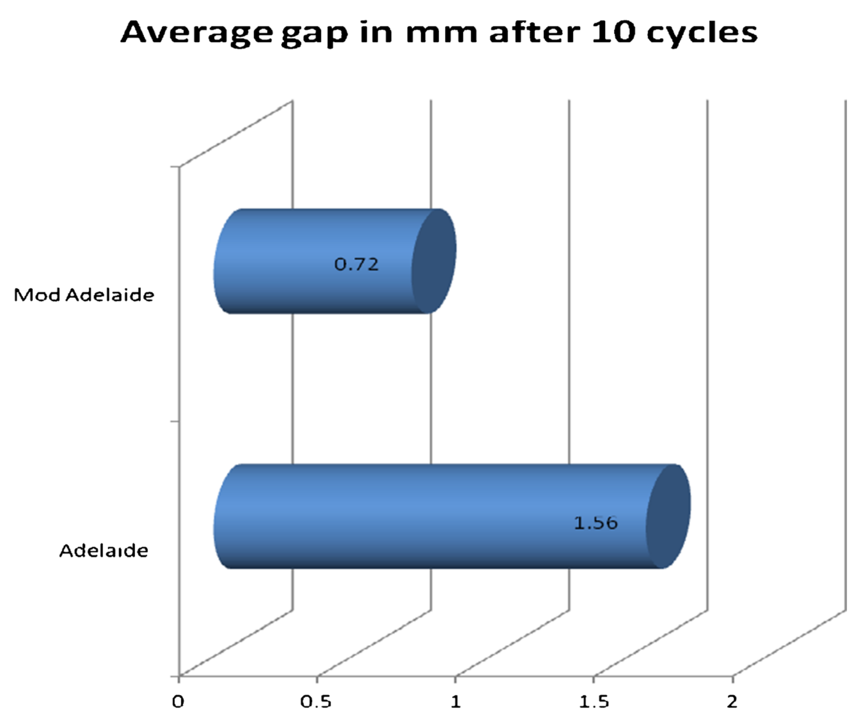
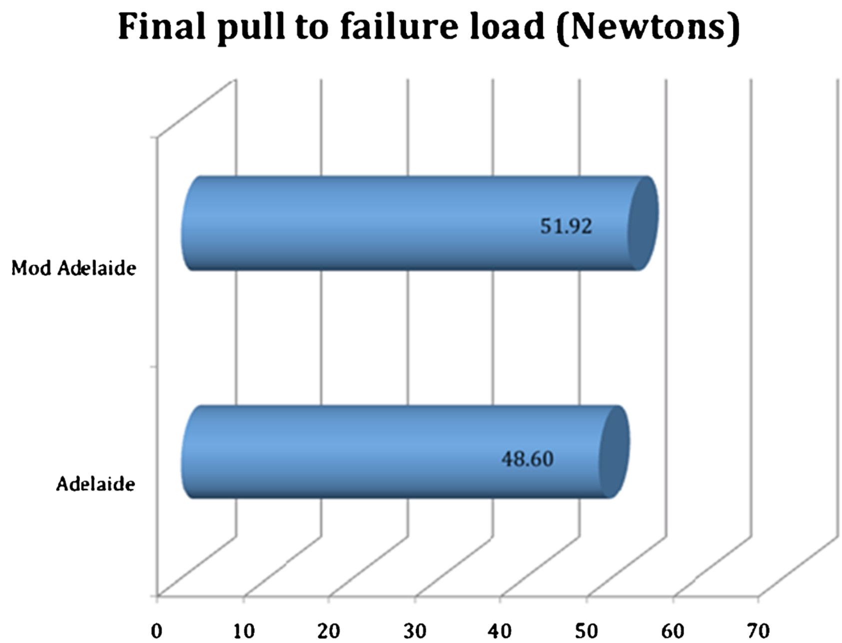


Fig. 7 Illustration of gapping in mm per cycle load

Fig. 8 Illustration of gapping in mm after ten loading cycles

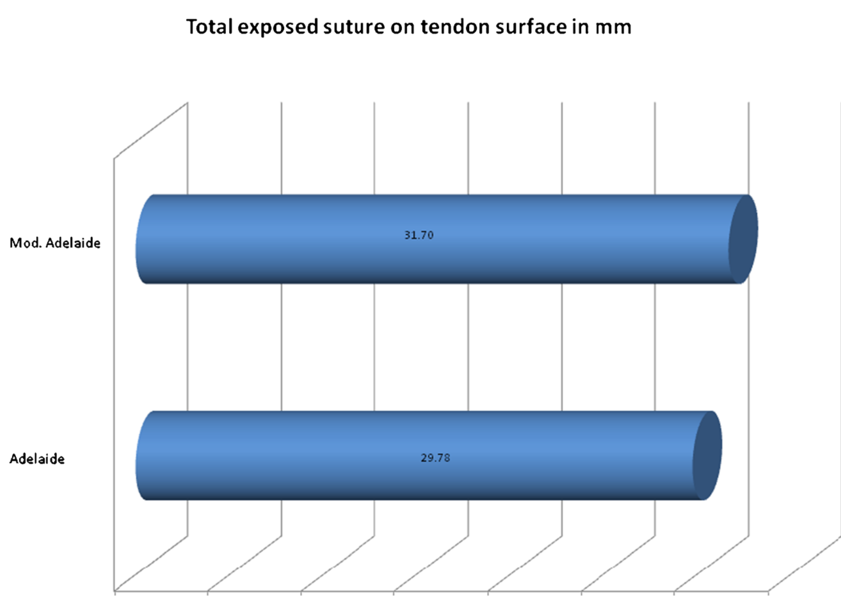


with this repair can have a significant impact on its biomechanical performance under load. We wanted to examine whether further modification in the form of interlocked cross stitches could confer additional benefits without unduly adding to repair time, complexity or bulk.

Dona et al. [27] demonstrated that in a 4 strand model, the addition of a simple looped epitendinous suture did not affect the load to failure, but significantly affected 2 mm gap force from 14 N to over 30 N. Therefore, we did not use a circumferential suture to avoid masking of differences in the performance of the two different core sutures. Our aim to recreate a clinical scenario as closely as possible led us to use a sheep tendon model which previous studies have proven to be more similar to human than porcine or bovine tendons when used in an ex-vivo laboratory experiment [23].

This experiment confirms earlier observations regarding the mechanism of gap formation in the Adelaide repair [19]. As the forces within the strands of the suture equilibrate, the tendon deforms in association with tightening of a single cross lock. This seems to be a critical event in gap formation. The resultant redundancy in the suture material leads to gap formation at the repair site. Our study proposes that by interlocking the cross locks of an Adelaide repair, the cross

Fig. 9 Total measured length of exposed suture on tendon surface in mm per group



lock's resistance to tightening under load may be increased and thus gap formation during early cyclic loading delayed.

Robertson and Al-Qattan [33] described a repair technique consisting of looped core strands in each half of the transected tendon that interlocked with each other between the cut ends of the tendon. They concluded that their repair was stronger and more resistant to gapping than the modified Kessler or Strickland techniques. However, their technique is a 6 strand repair requiring more tissue handling while placement of the interlocking loop between the ends of the divided tendon can make it difficult to tension the repair appropriately.

It is important to use a robust system to accurately measure gaps during testing. We think by measuring 8 distances across the whole gap for each repair at each testing phase and averaging these measurements we can achieve a precise and reliable method of measuring gaps, even if the gap forms asymmetrically.

The most notable biomechanical findings of this study are seen in the significant reductions in gap formation over the first 10 cycles of loading (Fig. 8). It has been demonstrated that gap formation during the early phase of cyclical loading may be critical to the overall biomechanical integrity of the repair [34]. It is also established that gap formation is associated with increased adhesion formation, decreased tendon gliding and poor clinical results [3–7]. The ultimate gap formation of both techniques after 250 loading cycles was over 3 mm which exceeds clinically acceptable levels but we feel that a great deal of this can be explained by the absence of an epitendinous suture. The significance of our results lies in the observation that gapping starts in the very earliest cycles of loading and the ability of the modified suture technique to resist this is significantly better. Therefore, interlocking the cross locks of an Adelaide tendon repair could allow improved healing conditions across a smaller gap during the initial rehabilitation period. Although the differences between groups seen in this study are relatively small, we believe that even a small reduction in tendon repair gapping may impact on final repair strength and functional outcome in a clinical setting. Regardless of these in vivo implications, our study could also show that a simple interlocking of suture components can improve suture constructs with regard to gapping. This is a potentially important development in our understanding of the structural integrity of tendon repair constructs.

We also demonstrated a modest increase in the final load to failure force although this did not reach statistical significance in our study. Our experiment measured ultimate failure forces following cyclic loading of the repaired tendon. Ultimate failure forces measured as a single load to failure without applying cyclic loads may not be a reliable indicator of the biomechanical performance of a particular tendon repair technique. It has been demonstrated that the ultimate load to failure of a repair significantly decreases after cyclic loading and differs from the single load to failure in a previously unloaded repair [35]. This emphasizes the importance of tendon gapping as a mode of failure as described by Gelberman [36]. The biomechanical behaviour of the repair during cyclic loading, especially gapping resistance, may be a more accurate representation of the repairs performance rather than the singular measurement of final failure forces.

The simple modification that we describe to this already proven technique does not seem to have any noticeable drawbacks. To perform this new repair is easy since the modified construct only requires a minor alteration of cross stitch placement. Additionally, we could show that the interlocking Adelaide repair does not add a significant amount of suture exposure on the tendon surface. Despite we did not specifically measure repair bulk in our experiment, we feel confident that the repair bulk remained the same since the overall repair configuration was only changed marginally. The issue of suture exposure and bulk is a crucial determinant when considering tendon friction and resulting adverse influences on work of flexion. Nevertheless our study focused on the repair stability of this new repair method, work of flexion was not measured.

Although there is a theoretical possibility that the suture may fail at the site of interlocking due to the friction of one strand over the other, this was not observed in our experience.

This experiment is a biomechanical laboratory study and our conclusions point towards improved tendon gapping and higher ultimate tensile strength in the modified repair technique, but improved tendon healing or adhesion formation can only be inferred. This study provides a platform for further work using an in-vivo model investigating healing propensities and final functional outcome of these different repair methods. It can also act as a platform to further investigate the concept of interlocking tendon repair techniques.

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