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A novel needleless graft-grasping suture (Ram Knot) for ACL reconstruction: a biomechanical study

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A novel needleless graft-grasping suture (Ram Knot) for ACL reconstruction: a biomechanical study

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Abstract

Background

This study describes the Ram Knot, a novel fully needleless graft-grasping suture technique for hamstring tendon autograft preparation in anterior cruciate ligament reconstruction (ACLR) comparing its biomechanical performance with the traditional whipstitch technique.

Methods

Porcine flexor tendons (n = 12) were standardised and randomly allocated to two groups: Ram Knot (RK) and whipstitch (WS) (n = 6 each). Specimens were subdivided into Single-Step Testing (SST) and Double-Step Testing (DST) protocols (n = 3 per subgroup). Biomechanical testing was performed using an Instron mechanical testing system and consisted of three phases: pre-tensioning (10–100 N), cyclic loading (200 cycles between 10–200 N), and load-to-failure testing. Outcome measures included ultimate failure load, elongation (E1–E3), stiffness, and failure mode.

Results

All specimens failed by suture rupture. There were no statistically significant differences in ultimate failure load or cyclic displacement between RK and WS groups. In SST conditions, WS demonstrated a higher mean failure load than RK (545.1 N vs 423.5 N), whereas in DST conditions RK demonstrated a higher mean failure load (382.5 N vs 359 N); these differences were not statistically significant. The RK demonstrated significantly greater stiffness ($p = 0.004$) and reduced elongation at failure (E3) ($p = 0.007$) compared with WS. Pre-tension elongation (E1) was also significantly lower in the RK group ($p = 0.025$). Qualitative analysis demonstrated minimal slippage of the primary loop in RK constructs, whereas WS constructs exhibited progressive tendon damage at the suture–tendon interface.

Conclusion

The Ram Knot demonstrates biomechanical performance comparable to the traditional whipstitch technique, with significantly increased stiffness and reduced elongation. In addition, it provides practical advantages including faster graft preparation, elimination of needle passes, and reduced tendon damage. These findings suggest that Ram Knot represents a mechanically reliable and efficient alternative for hamstring graft preparation in ACL reconstruction.

Introduction

Anterior cruciate ligament reconstruction (ACLR) is among the most frequently performed orthopaedic procedures, with reported incidences ranging from 4.1 to 51.3 per 100,000 population [1]. Although a variety of graft choices and fixation techniques can be employed, the use of hamstring tendon (HT) autograft secured with a cortical button proximal on the femur and an interference screw distally on the tibia remains the most commonly utilised construct [2].

During this technique, the graft is initially anchored within the femoral tunnel using a cortical suspensory device. A traction suture is then applied to the free end of the graft to facilitate handling and maintain appropriate tension during tibial fixation with an interference screw.

Traditionally, graft preparation has relied on locking suture techniques such as the Krackow, baseball, or whipstitch methods. These techniques require multiple needles passing through the tendon, which can induce microtrauma, potentially compromising the structural and mechanical integrity of the graft [3]. This damage may predispose the construct to elongation or suture slippage under load [4, 5].

To address these concerns, several alternative graft-grasping suture techniques have been described, including the Modified Finger-Trap [6], Modified Rolling Hitch [7], Wittstein Suture Loop [8], and Modified Prusik Knot [4]. These techniques aim to reduce the number of needles passing through the tendon compared with traditional locking sutures such as the Krackow or whipstitch. However, many of these constructs still require at least one pass of the suture through the tendon to secure the configuration. Techniques that minimise tendon penetration may help preserve graft integrity and improve efficiency during graft preparation. Biomechanical studies have demonstrated that these approaches can provide mechanical performance comparable to traditional locking sutures, and in some cases superior performance under tensile loading [9].

The objective of this study was to describe the “Ram Knot,” a novel fully needleless grasping suture technique for hamstring graft preparation in ACL reconstruction, and to compare its biomechanical properties with those of the commonly used whipstitch technique, utilising porcine flexor tendons as a surrogate model.

Materials and Methods

Specimen Preparation

Porcine superflexor tendons were harvested from porcine hind limbs obtained from an abattoir within 24 hours post-mortem. The animals were not bred, maintained, subjected to experimental procedures, or euthanised for the purposes of this study; the tissues were obtained post-mortem following slaughter unrelated to the research. Tendons were carefully dissected free of non-tendinous tissue, wrapped in tissue paper soaked with phosphate-buffered saline (PBS), sealed in plastic bags, and stored at −19 °C. Specimens were thawed 24 hours prior to biomechanical testing. Porcine flexor tendons were selected for their well-defined anatomy, ease of harvesting, and prior validation in biomechanical research [6, 10, 11].

Tendons were standardised to 18.5 ± 0.5 cm length and trimmed to a uniform diameter of 6.5 ± 0.5 mm, confirmed using a graft sizer (DePuy, Leeds, UK). Twelve samples were randomly assigned to two groups (n=6 each): Ram Knot (RK) and Whipstitch (WS) [fig. 1]. Suturing was performed by a consultant orthopaedic surgeon using Number 5 Ethibond braided polyester suture (Ethicon, Summerville, NJ). RK samples received a RK approximately 3 cm from each tendon end. WS samples were armed with a six-throw whipstitch of uniform pitch. Specimen hydration was maintained throughout preparation and testing by intermittent PBS application.

Technique for performing the RK was as follows [fig. 2]; the suture is first folded in half, creating a loop at the midpoint. This suture is positioned beneath the graft, with the loop on one side and the two free ends on the opposite side. The loop is then brought over the top of the graft, and the two free ends are passed through the loop from underneath the graft. Next, the two free ends are then wrapped over the graft and passed through the loop a second time from underneath, then pulled simultaneously to cinch and secure the knot tightly against the graft. To maintain tension and stability, two single throws of a reef knot are tied using the two free ends of the suture.

Biomechanical Testing

Testing was performed using an Instron 3366 mechanical testing system (Instron, USA) equipped with a 1 kN load cell and controlled via Bluehill software (version 2.31). Data acquisition occurred at 10 Hz. Prior to testing, all specimens were preloaded to 1 N.

Each sutured tendon was suspended at its midsection by a custom fixture attached to the Instron crosshead. The four free suture ends were looped and secured around a stationary 10 mm diameter steel post to evenly distribute load and prevent rotational artifacts [Fig. 3].

The testing protocol, adapted from previous studies [6, 12, 13], consisted of three phases: pre-tensioning (phase I), cyclic loading (phase II), and load-to-failure testing (phase III). Pre-

tensioning involved three cycles between 10 and 100 N and was used to eliminate viscoelastic slack and simulate clinical graft preconditioning [14, 15].

Cyclic loading consisted of 200 cycles between 10 and 200 N at a displacement rate of 3.3 mm/s. The cyclic loading range (10–200 N) was selected to approximate physiologic forces that may be experienced by the graft during early postoperative rehabilitation [12].

Following cyclic loading, specimens underwent load-to-failure testing at the same displacement rate. Load-to-failure testing was performed to determine the ultimate strength of each construct and to identify the mode of mechanical failure.

Ultimate failure load and failure mode (rupture or pullout) were recorded. Elongation values (E1, E2, E3) were measured during each phase [Fig. 3]. Tendon stiffness was determined from the slope of the linear region of the load–displacement curve during phase III [Fig. 4].

Study Design

To evaluate the performance of the suture techniques more comprehensively, both Single-Step Testing (SST) and Double-Step Testing (DST) protocols were employed. SST simulates clinical conditions, with the same suture construct remaining in place throughout all phases of testing: pre-tensioning (Phase I), cyclic loading (Phase II), and load-to-failure testing (Phase III).

In contrast, DST was used to reduce variability between tendon specimens and allow clearer assessment of the suture construct itself. In this protocol, tendons were first preconditioned using a temporary Ram Knot and subjected to pre-tensioning (Phase I) and cyclic loading (Phase II). The temporary suture was then removed, and the assigned suture technique (Ram Knot or whipstitch) was applied prior to the final load-to-failure test (Phase III). By standardising the mechanical behaviour of the tendon before final testing, this approach reduces the influence of tendon variability and allows a more controlled comparison of the suture techniques.

Both RK and WS groups were subdivided into SST and DST subgroups (n = 3 each). In SST specimens, the assigned suture technique remained in place throughout all phases of testing (Phases I–III). In DST specimens, tendons were initially sutured 2 cm from the tendon ends using a Ram Knot for the preconditioning phases (Phases I and II). The temporary sutures were then removed and the tendons were re-prepared according to group assignment (Ram Knot at 3 cm or whipstitch) prior to the final load-to-failure test (Phase III) [Fig. 5].

Statistical Analysis

Data were analysed using multivariate analysis of variance (MANOVA) with statistical significance set at $\alpha = 0.05$ (SPSS version 21, IBM Corp., Chicago, IL, USA). Tukey's post hoc test was applied where appropriate to identify pairwise differences between groups. Data visualisation was performed using boxplots generated in Minitab (version 16, Minitab Inc., State College, PA, USA).

The null hypothesis was that there would be no significant difference in biomechanical performance between the Ram Knot and whipstitch techniques or between the two testing protocols (Single-Step Testing and Double-Step Testing).

Sample size was determined based on previously published biomechanical studies evaluating graft–suture constructs for anterior cruciate ligament graft preparation. Such studies commonly utilize between five and eight specimens per group due to the controlled conditions of laboratory testing and the relatively low variability associated with standardized tendon models [6, 11, 12]. A total of twelve specimens was therefore considered sufficient to allow comparison between techniques while remaining consistent with established biomechanical testing methodologies.

Results

All specimens failed due to suture rupture. In the Ram Knot (RK) group, failure typically occurred at or near one of the tightened knots. In contrast, the Whipstitch (WS) group exhibited suture breakage distal to the tendon end, often adjacent to the steel post.

No statistically significant differences were observed between the two suture techniques with regard to ultimate load to failure or displacement during cyclic loading (E2). Within the Single-Step Testing (SST) protocol, the WS subgroup demonstrated a higher mean failure load compared with the RK subgroup (545.1 N vs 423.5 N, respectively). Conversely, within the Double-Step Testing (DST) protocol, the RK subgroup demonstrated a slightly higher mean failure load than the WS subgroup (382.5 N vs 359 N). However, these differences did not reach statistical significance.

Under SST conditions, the Ram Knot demonstrated significantly greater stiffness ($p = 0.043$) and reduced elongation at failure (E3) ($p = 0.040$) compared with the whipstitch. When comparing suture techniques overall, the RK group demonstrated significantly higher stiffness ($p = 0.004$) and lower E3 values ($p = 0.007$). In addition, mean pre-tension elongation (E1) was significantly smaller in the RK group compared with the WS group ($p = 0.025$).

When comparing testing protocols, SST demonstrated greater mechanical performance than DST for both suture techniques. Detailed mechanical property data for each technique are presented

in Tables 1 and 2 and Figure 6. Load–extension curves for all 12 samples are illustrated in Figures 7 and 8.

Qualitative observations revealed minimal slippage of the primary suture loop in RK specimens, with the knot remaining at the original fixation point throughout testing. Most displacement appeared to result from slippage at the secondary securing throws [Fig. 9]. In contrast, WS specimens frequently demonstrated partial shredding at the tendon–suture interface, where distal suture throws progressively incised the tendon under increasing load [Fig. 10]. Statistical comparisons between groups are summarised in Table 3.

Discussion

This biomechanical study evaluated a novel needleless graft-preparation technique, the Ram Knot, for hamstring tendon autografts used in anterior cruciate ligament reconstruction (ACLR). The principal finding was that the Ram Knot demonstrated biomechanical performance comparable to that of the traditional whipstitch technique. Ultimate failure loads were statistically equivalent between the two constructs, and both substantially exceeded the forces typically encountered during graft passage and fixation. In addition, the Ram Knot demonstrated greater construct stiffness and reduced elongation under certain testing conditions. These findings suggest that the Ram Knot provides a mechanically reliable alternative to conventional whipstitch suture techniques while offering several practical advantages during graft preparation.

Biomechanical Performance

The mechanical properties of graft–suture constructs influence graft handling and tensioning during ACL reconstruction. In the present study, both the Ram Knot and whipstitch constructs demonstrated failure loads well above those required during graft passage, graft tensioning, and early physiological loading.

Typical graft tension during anterior cruciate ligament reconstruction has been experimentally evaluated in the range of approximately 44–89 N [16]. In addition, pretensioning of soft-tissue grafts is sometimes performed during graft preparation, with commonly reported pretensioning loads in the range of approximately 80–89 N [17].

Although sutures are primarily intended to provide traction during graft passage tensioning and fixation, they may occasionally be retained as secondary or backup fixation. In such circumstances, the sutures may be subjected to physiological loads transmitted through the graft during early postoperative activity. ACL forces during common functional activities have been estimated to reach approximately 200–250 N [18].

The constructs tested in our study failed at loads exceeding 350–500 N, indicating that both techniques provide more than sufficient mechanical strength to withstand pretensioning during graft preparation, traction during graft fixation, and physiological loading if retained for secondary fixation.

Although ultimate strength was similar between groups, the Ram Knot demonstrated significantly higher stiffness with reduced elongation at failure under Single-Step Testing conditions. Excessive graft elongation may result in loss of graft tension and contribute to increased laxity. Elongation greater than 3 mm has been associated with clinically detectable anterior laxity postoperatively [19]. Therefore, constructs demonstrating reduced elongation, such as the Ram Knot, may contribute to improved graft stability.

Qualitative observations during testing support these findings. In the Ram Knot group, the primary circumferential loop remained securely positioned around the tendon throughout loading, with minimal migration of the grasping loop. Most displacement appeared to occur at the secondary securing throws rather than through slippage of the primary loop. In contrast, whipstitch constructs frequently demonstrated progressive tendon damage at the tendon–suture interface, where distal suture throws gradually incised the tendon under increasing load. Similar patterns of tendon damage associated with whipstitch techniques have been reported in previous biomechanical studies [6, 11].

Previous biomechanical studies have shown that alternative grasping techniques can achieve mechanical properties comparable to traditional locking sutures. Zhang et al. [9] demonstrated differences in elongation and failure load across continuous-loop graft preparation techniques, while Diaz et al. [20] reported greater stiffness and ultimate failure load with a whip-lock stitch than with a whipstitch in semitendinosus tendons. Likewise, Krappinger et al. [4] observed increased construct stiffness with circumferential grasping techniques such as the modified Prusik knot. Although these techniques reduce the number of needle passes required for graft preparation, many still involve some degree of tendon penetration to secure the construct. In contrast, the Ram Knot achieves circumferential graft fixation without requiring any suture passage through the tendon.

Taken together, these findings suggest that the Ram Knot provides biomechanical performance comparable to traditional locking suture techniques while maintaining stable tendon engagement during loading.

Practical Advantages

Beyond its biomechanical performance, the Ram Knot offers several practical advantages during hamstring graft preparation. The technique is simple to perform and can be applied rapidly without the need for multiple needle passes through the tendon. In the present study, the Ram

Knot could be tied in less than 20 seconds, whereas traditional whipstitch techniques may require approximately 90 seconds to prepare each graft limb. This represents an approximate 80% reduction in preparation time per graft end while maintaining comparable biomechanical performance.

Improved efficiency during graft preparation may be particularly beneficial in high-volume surgical environments, where small reductions in preparation time can contribute to shorter operative times and improved operating theatre workflow. Similar time-saving advantages have been reported with other reduced-needle or needleless graft preparation techniques, including the modified finger-trap technique [6], the WhipKnot [21], and the Wittstein loop [8].

Another advantage of the Ram Knot is the elimination of needles passing through the tendon. Conventional locking techniques such as the whipstitch or Krackow require repeated suture penetration of the graft, which may introduce localised tendon damage and longitudinal fibre disruption. Experimental studies have demonstrated that repeated suture penetration can weaken tendon fibres and increase the risk of suture pull-through [3, 4]. By securing the graft using circumferential compression rather than tendon penetration, the Ram Knot may help preserve the structural integrity of the graft during preparation.

In addition, circumferential grasping of the tendon may allow load to be distributed more evenly around the graft compared with locking sutures that concentrate stress at discrete penetration points. This mechanism may explain the reduced tendon damage observed in the present study and may contribute to more consistent graft engagement during traction and fixation. Taken together, these characteristics suggest that the Ram Knot provides a simple and efficient method for hamstring graft preparation while maintaining biomechanical properties comparable to, and in some respects superior to, traditional whipstitch techniques.

Limitations

Several limitations of this study should be acknowledged. Porcine flexor tendons were used as a surrogate model for human hamstring autografts. Although this model is commonly used in biomechanical research and provides a consistent and reproducible testing substrate, differences in tissue composition, geometry, and viscoelastic properties may limit direct extrapolation of these findings to human grafts.

The sample size was relatively small, particularly within subgroup analyses (n = 3), which limits statistical power and increases the risk of type II error. However, this is consistent with previously published biomechanical studies evaluating graft–suture constructs, which commonly utilise small, controlled sample sizes due to the low variability of standardised tendon models [4, 6, 11]. Larger studies are required to confirm the trends observed in this investigation.

Biomechanical testing was performed using uniaxial tensile loading in a laboratory setting, which does not fully replicate the complex, multidirectional forces experienced by graft constructs in vivo during knee motion and rehabilitation.

Elongation measurements were based on crosshead displacement, which incorporates deformation of the tendon, suture material, and knot configuration. This method may therefore overestimate true graft elongation.

In addition, graft preparation was performed manually without the use of a standardized graft preparation board or tensioning device, which may have introduced variability in suture placement and applied tension, particularly for the whipstitch technique.

Conclusion

The Ram Knot is a simple, needleless technique for hamstring graft preparation in anterior cruciate ligament reconstruction. In this biomechanical study, it demonstrated mechanical strength comparable to the traditional whipstitch technique, while exhibiting favourable stiffness and elongation characteristics. The construct exceeded the mechanical demands typically encountered during graft passage, fixation, and early physiological loading.

In addition to equivalent biomechanical performance, the Ram Knot offers practical advantages, including faster graft preparation, elimination of needle passes through the tendon, and potentially reduced tendon damage. These characteristics suggest that the Ram Knot may represent a mechanically reliable and efficient alternative to traditional locking suture techniques for graft preparation in ACL reconstruction.

The senior author has used this technique clinically for four-strand hamstring graft preparation for over a decade; however, clinical outcomes were not formally evaluated in the present study.

Declarations

Ethics approval and consent to participate

Not applicable. This was an ex vivo biomechanical study using porcine tendon tissue obtained post-mortem from an abattoir. The animals were not killed or subjected to any experimental procedure for the purposes of this study; only tissues obtained after death were used. No procedures were performed on live animals as part of this research. Therefore, approval for experiments involving live animals was not applicable to this study.

Consent for publication

Not applicable. No identifiable patient information or patient images are included in this manuscript.

Availability of data and materials

The datasets generated and/or analysed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

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Author contributions

Ram Venkatesh contributed to the original idea for the study and conduct of the study. Tobi Oputa contributed to the design and conduct of the study. Abhishek Kumar Singh contributed to completion of the manuscript, editing and publication preparation. Haneen Aldulaimi contributed to analysis and data interpretation. Rohit Rambani contributed to manuscript development. Todd Stewart contributed to analysis and data interpretation. All authors reviewed and approved the final manuscript.

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	Ram Knot		
	SST	**DST**	**Total**
Failure Load (N)	423.5 (88)	382.5 (44.1)	403 (66.2)
E1 (mm)	6.7 (1.1)	8.7 (1.8)	7.8 (1.8)
E2 (mm)	22.2 (5.2)	28.1 (8.5)	25.1 (7.1)
E3 (mm)	17.5 (5.3)	41.8 (4.3)	29.7 (14)
Stiffness (N/mm)	23.5 (3.5)	8.9 (0.5)	16.2 (8.3)

Table 1: Mechanical properties – mean (standard deviation) - of the Ram knot group

	Whipstitch		
	SST	**DST**	**Total**
Failure Load (N)	545.1 (101.2)	359 (71.7)	452.1 (128.6)
E1 (mm)	11.7 (8.4)	7.5 (1.8)	9.6 (5.9)
E2 (mm)	23 (12.2)	23.4 (2.9)	23.2 (8)
E3 (mm)	34.9 (8.6)	34.8 (4)	34.8 (6)
Stiffness (N/mm)	14.7 (3.9)	10.3 (1.7)	12.5 (3.6)

Table 2 Mechanical properties – mean (standard deviation) - of the Whipstitch group

	P Value				
	Failure Load	**E1**	**E2**	**E3**	**Stiffness**
RKSST × RKDST	0.510	0.132	0.362	0.003*	0.002*
RKSST × WSSST	0.191	0.360	0.919	0.040*	0.043*

RKDST × WSDST	0.655	0.369	0.414	0.107	0.245
WSSST × WSDST	0.060	0.439	0.962	0.982	0.153
RK Total × WS Total	0.169	0.025*	0.946	0.007*	0.004*

Table 3: **Statistical significance (confidence interval = 95%) between the test modes based on the suture technique, and between the suture techniques based on the test mode. The asterisk (*) indicates statistical difference since p-value is less than 0.05.**

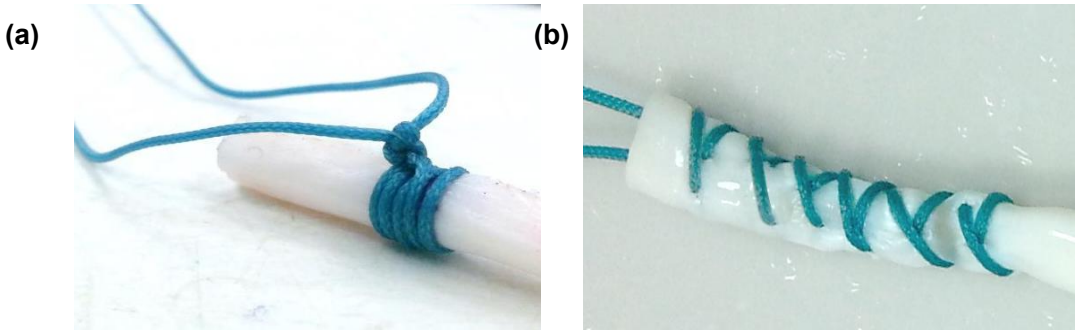


Figure 1: The configurations of (a) Ram Knot and (b) Whipstitch

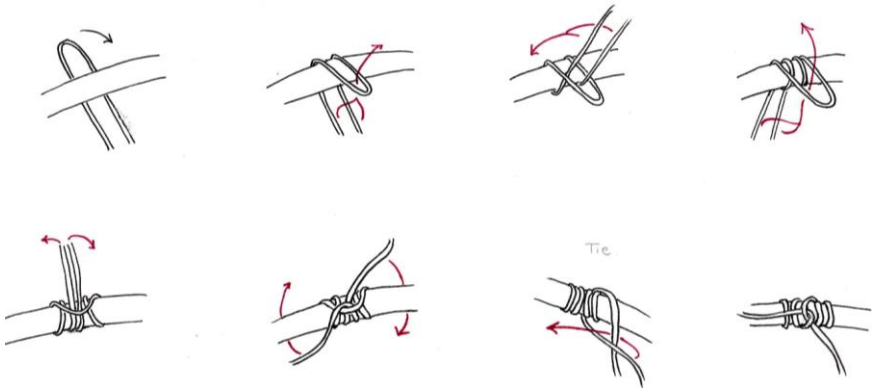


Figure 2: Schematic diagram representing the technique of tying the Ram knot

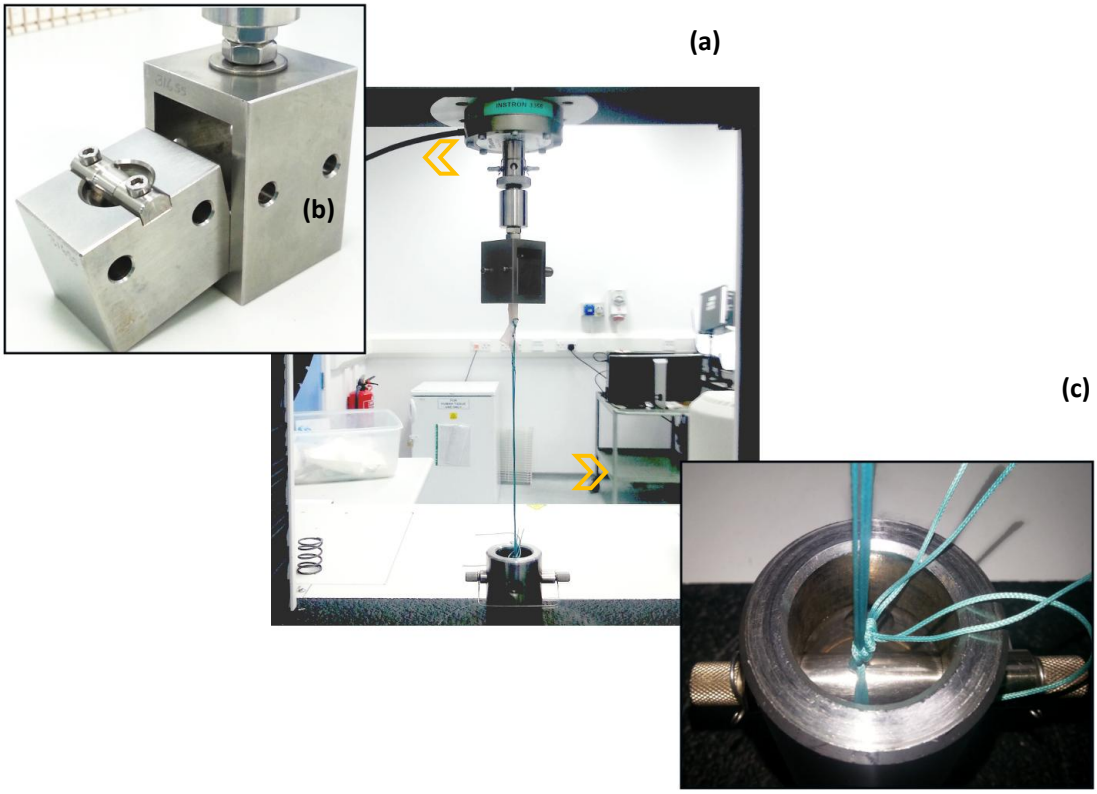


Figure 3 Experimental set-up: (a) test configuration; (b) fixture device; (c) attachment method

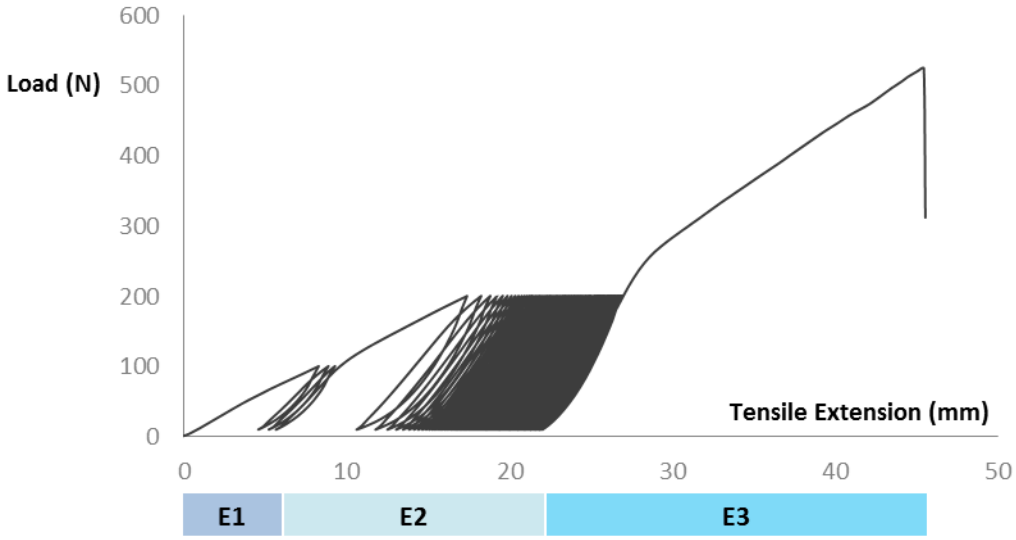


Figure 4: Load-displacement graph for one of the samples illustrating the three phases and the corresponding elongation for each phase.

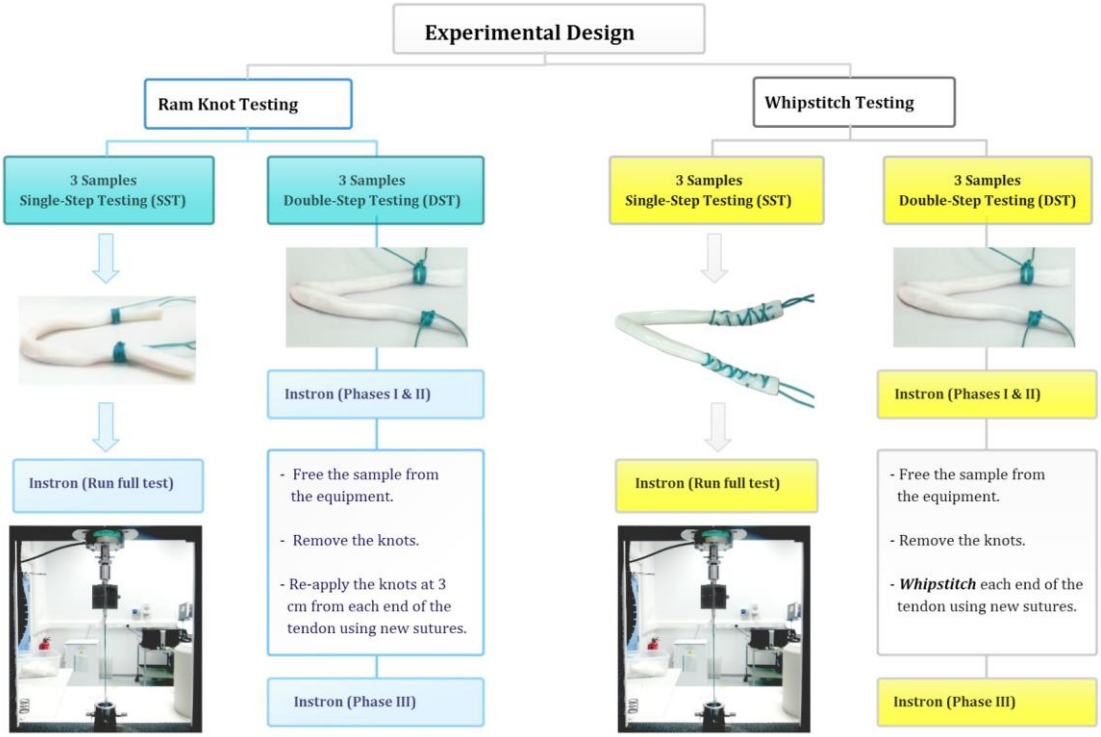


Figure 5: Flowchart summarising study protocol

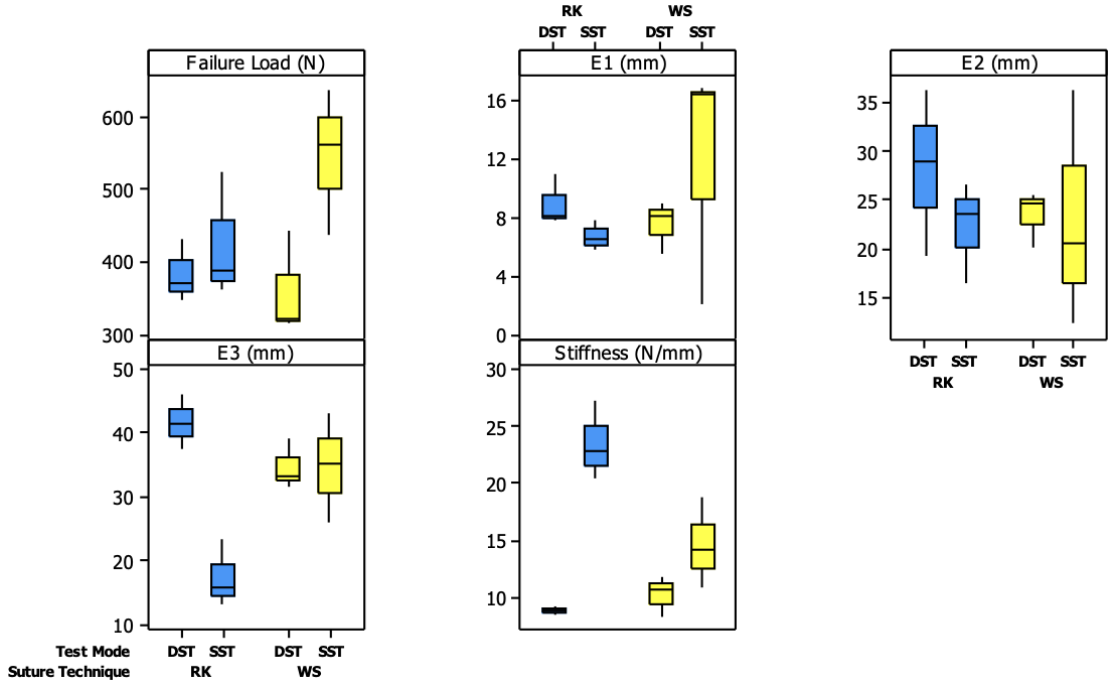


Figure 6: Boxplots of failure loads, stiffness and elongation results for each test group

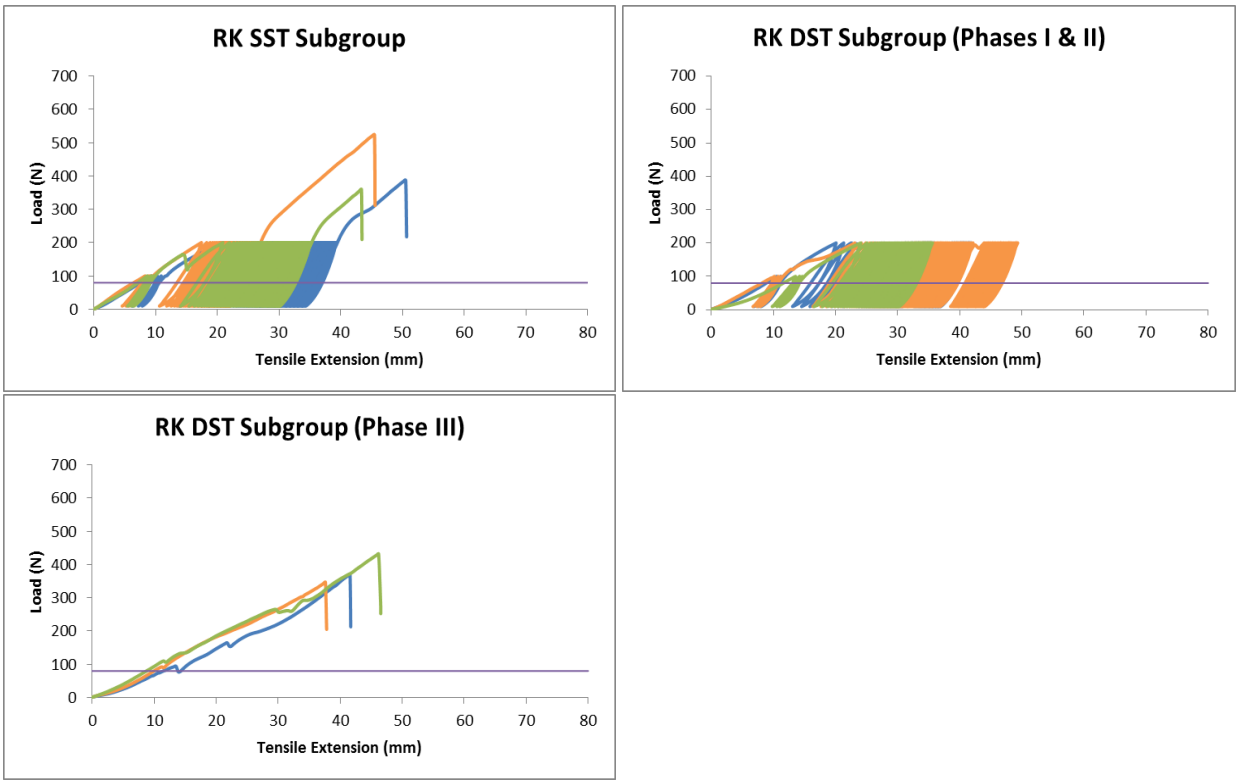


Figure 7: Graphs of load (N) against tensile extension (mm) of RK samples. The horizontal line at 80 N is shown as a reference pretensioning load reported in prior soft-tissue graft literature [17].

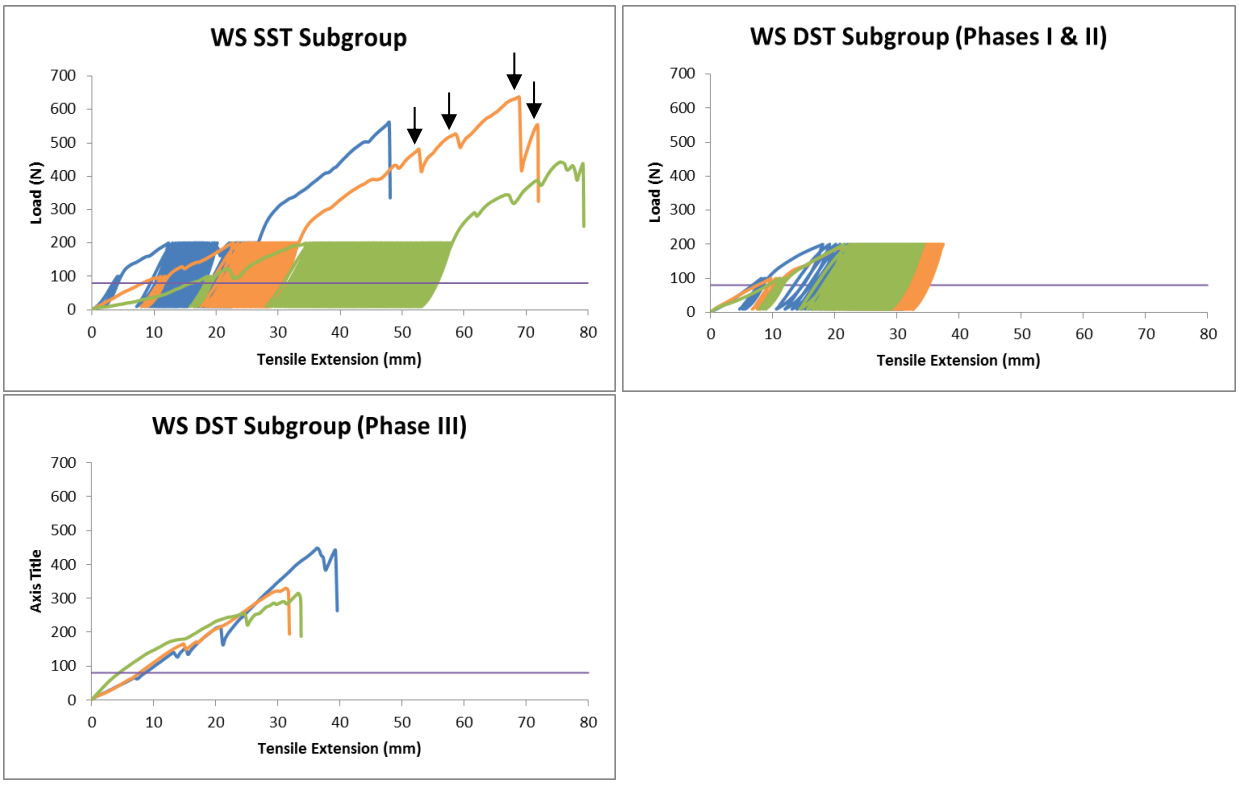


Figure 8: Graphs of load (N) against tensile extension (mm) of WS samples. The arrows point at the multiple peaks present during phase III of the test.

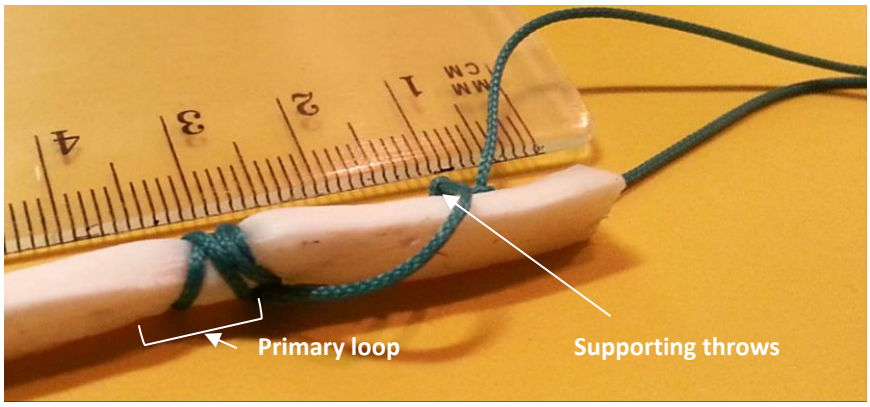


Figure 9: An image of a sample from the RK group after the mechanical testing demonstrating how the position of main loop remained somewhat unaltered (at 3 cm) even after the test.

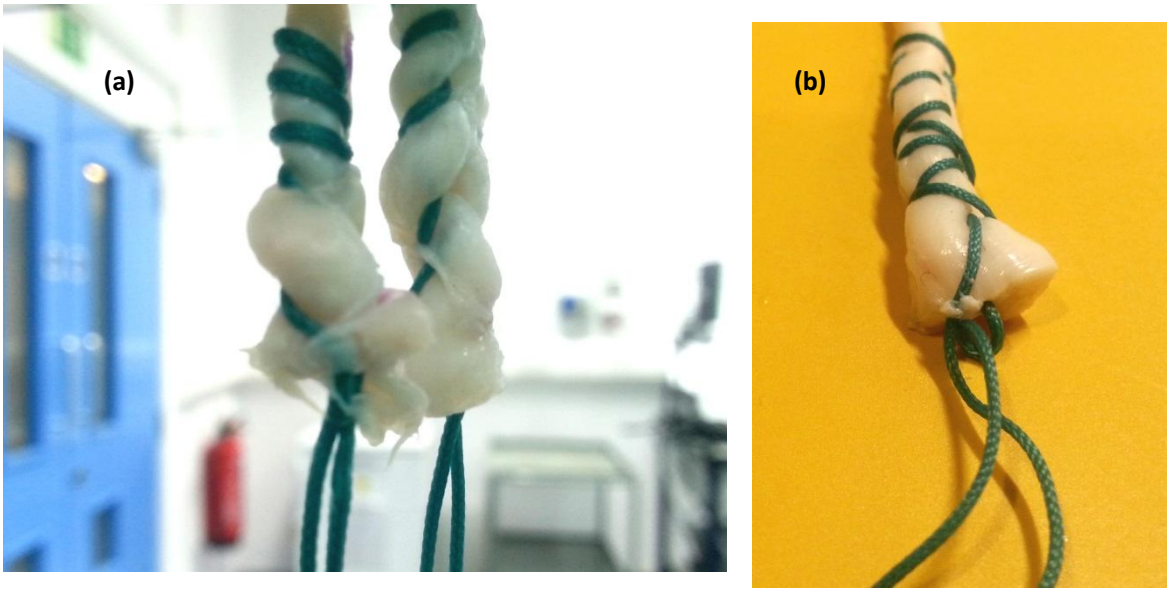


Figure 10: Samples from the WS group after testing: (a) Partial tearing of the tendon; (b) Tearing and subsequent loosening of the suture throw