Effect of Suturing of a Tendon Graft in ACL Reconstruction

Chizari M., Wang B. and Snow M.

Abstract—**Permanent viscoplastic elongation in response to cyclic loading in the early postoperative period might affect a sutured graft function. The objective of this study is to test the hypothesis that suturing of a tendon graft may affect the material properties of the corresponding tendon site, due to local changes in tendon matrix composition. Several digital flexor tendons were armed with a whipstitch and examined under tension or cyclic loading. In parallel a 3D numerical modelling was performed to analyse the mechanical behaviour of the sutured tendon. The experimental data and numerical evaluation show suturing of tendon graft has no significant effect on the mechanical properties of the graft for the application of ACL reconstruction. In general no correlation was found between suturing and the material properties of the tendon segments.**

***Index Terms*—ACL reconstruction; tendon graft; suture; load-to-failure; cyclic loading.**

I. INTRODUCTION

Anterior cruciate ligament (ACL) rupture is a common knee injury. Restoration of the ACL function is very important, with ACL reconstruction using autografts currently being the preferred technique [1-3]. The most commonly used graft is hamstring tendon grafts which has lower donor-site morbidity and allow multiple bundle reconstruction [4-6].

Appropriate graft tension and secure graft incorporation in bone tunnels are essential for successful ACL reconstruction using hamstring tendon grafts. In the early postoperative period graft fixation is the mechanically weak link within the entire system [7]. No commonly used graft fixation device has mechanical properties comparable with the intact ACL [4,5]. Therefore, fixation methods must be rigid and stiff to withstand mechanical loading during daily activities, which are estimated as 454 N at most [8], and allow current rehabilitation principles.

It has been suggested that permanent viscoplastic elongation of the graft constructs in response to cyclic loading in the early postoperative period might negatively affect graft function [9]. It occurs in particular with the use of indirect fixation devices such as the endobutton/polyester tape or screw post-fixation. Furthermore, fixation devices of soft tissue grafts have to facilitate biologic incorporation by providing a large free contact area between tendon and bone tunnel wall [10].

The objective of this study was to investigate the mechanical behaviour of a sutured tendon graft using the whipstitch technique in the load-to-failure, and cyclic loading tests [11]. We are hoping to achieve a better understanding of the mechanics of a sutured tendon, applicable to ACL reconstructions.

The paper uses an experimental and numerical method to elucidate the mechanics of the sutured tendon in a bovine model, in particular to investigate the strength of the tendon-suture junction under mechanical loading. A three-dimensional finite element model (using the commercial finite element code Abaqus 6.7) has been developed to analyse the mechanical characters of the sutured tendon under a tensile loading.

II. MATERIAL AND METHODS

Bovine hoof digital flexor tendons were used for the load-to-failure test and the cyclic loading tests. Specimens were kept moist with saline spray during all preparations and testing. Using an Arthrex Speed Whip® 2.0 suture, the tendons were armed with a whipstitch. The suture cross section was 0.283 mm^2 (Fig. 1). The test was done in three stages; firstly testing the maximum tensile load of the suture material, secondly testing the strength of suture-tendon junction under mechanical loading.

Initially few loop sutures was tested under a tensile load to obtain the strength of the suture itself. The loop suture was clamped rigidly in the test rig and loaded at a loading rate of 5 mm/sec. The data recorded in form of load-displacement and the mode of failure was determined visually.

Following the suture testing, the sutured tendon was tested. The prepared whip stitched tendon specimen was clamped to the testing machine and loaded to failure at a rate of 5 mm/sec. The total length of the tendon specimens were 160 mm, the average cross section was 3.90 mm^2. A tensile load was applied at a constant displacement rate of 1 mm/s, which is a standard testing mode for ACL fixation devices [12-16].

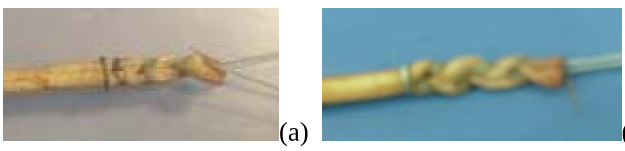

(a) (b)

Fig. 1. The sutured region of a bovine digital flexor tendon before (a) and after (b) loading. The deformation of the tendon can be seen in the sutured area.

Manuscript received April 4, 2009.
Mahmoud Chizari, School of Engineering, University of Aberdeen, Aberdeen, UK (corresponding author, Mobile: +447886454320; e-mail: mahmoudchizari@yahoo.com).
Bin Wang, School of Engineering, University of Aberdeen, Aberdeen, UK.
Martyn Snow, Department of Orthopaedics, The Royal Orthopaedic Hospital, Birmingham, UK .

While loading the specimens, the displacements and forces were recorded and slippage of the suture and deformation of the tendon in the sutured region were monitored. Stiffness was determined by using a linear regression employing data. The slope of the regression line was defined as stiffness in N/mm. The mode of failure was also determined.

Along with load-to-failure test a cyclic loading test also was performed on a loop tendon. The two ends of the tendon were overlapped and whip stitched for 20 mm. The total length of the tendon loop was 50 mm. The tendon loop was secured to a testing machine using a custom built clamp. The suture part of the graft was kept in the middle length between the clamps. A preload of 10 N was applied for 1 min then the resulting displacement was set to zero. A small tape marker was set on the loop next to the clamp in order to recognize initial length of sutured and unsutured parts of the loop.

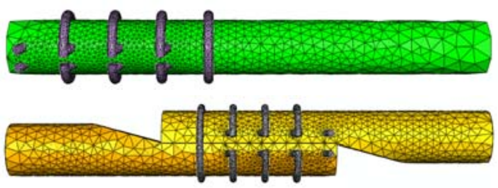
The specimens were loaded accordant to a the previously proposed loading protocol for 100 cycles from 10 to 50 N followed by 100 cycles from 10 to 75 N at a rate of 0.5 Hz [12,17]. The tendon response to the loading was documented.

III. Finite Element Modelling

In order to understand factors that influence the deformation of the tendon at the sutured site, a 3D numerical model using finite element analysis was created to simulate the tensile tests that were performed. The model of the tendon was geometrically simplified and tetrahedral elements allowing for large deformation were used. The mesh was locally refined in the vicinity of the interface between the suture and tendon. The FE model of the sutured tendon one end and suturing two ends of the tendon was modelled, Fig 2.

The boundary condition defined in the analysis allows transmission of the load between the suture and the tendon. The friction coefficient between tendon-suture and tendon-tendon was assumed 0.1 and 0.05 respectively [18]. A pure tensile loading was applied to the free ends of the sutures.

The model focuses on the early stage deformation and no failure mode has been introduced. It assumes an isotropic, homogeneous and linear elastic behaviour for the tendon, which is adequate for the study of stress and deformation [18]. Also an isotropic Poisson's ratio was used for the tendon.



(a)

(b)

Fig. 2. FE model of the sutured tendon. Only one end of the tendon has been modelled.

IV. Results

A. Loop suture; tensile test

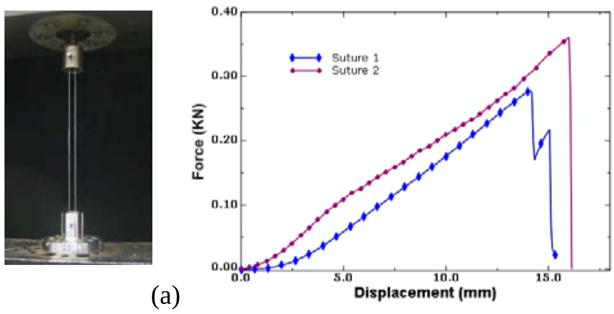
The loop sutures were tested successfully in the load-to-failure test. There was a snap type fracture and the failure location was unpredictable, but often occurred in the vicinity of the grip edge. Fig. 3 shows experimental setup of the test and load-displacement result of two samples.

B. Sutured tendon; load to failure test

Three samples were tested. The tendon showed immediate stretching [19]. The tendons failed at the suture/tendon interface as sutures cut into the tendon and eventually broke the tendon (Fig. 4). There were no snap type fractures. Failures were due to a progressive breakage of the tendon fibers. In general the mechanism of failure was slippage of the suture at the first suture throw and tearing of the first knot through the most distal portion of the tendon. The time of suture rupture was identical with the time of maximum force. The force-displacement curve after that incident was sharply dropped to zero. The maximum failure loads of the specimens were recorded as 238, 379 and 429N as shown in Fig. 5.

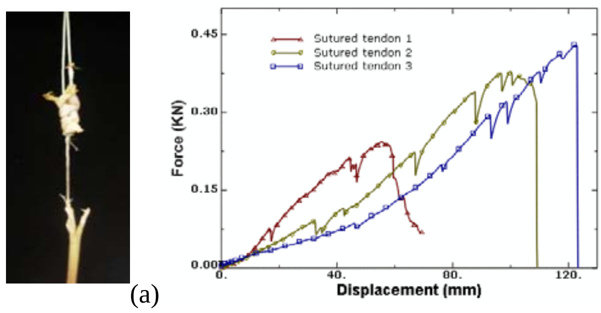
C. Sutured tendon; cyclic test

Several specimens were tested successfully for 200 cycles in the cyclic loading test with no suture rupture or other failures. The displacement on the first few cycles was significantly bigger compare to the displacement after the fifth cycle this also was reported previously by others [20]. This displacement reset and defined as zero. No significant differences were found for the other parameters in the cyclic loading test.



(a) (b)

Fig. 3. Experimental setup of the test (a); and load-displacement result of two rigidly clamped looped sutures.



(a) (b)

Fig. 4. Failure of the sutured tendon usually occurred in the sutured region starting from the distal end of the region during tensile loading (a); load-displacement result of the three sutured tendon under tensile loading (b)

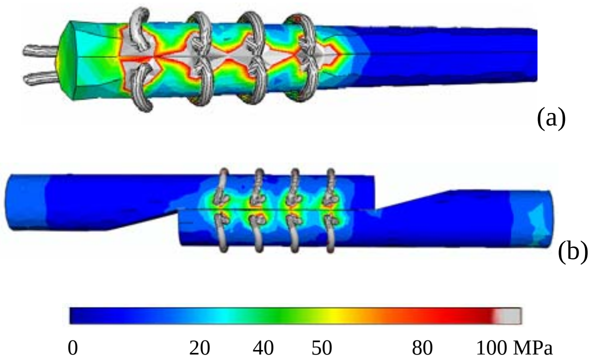


Fig. 5. FE stress analysis result of the sutured tendon under tensile test. The colours define the level of Mises stress on the suture and tendon.

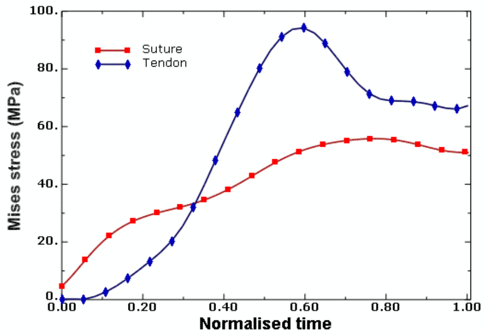


Fig. 6. Numerical Mises stress result of the sutured tendon under a tensile loading.

D. Numerical evauation

The result of the stress analysis of the sutured tendon under tensile loading is shown in Fig. 5. The pattern of Mises stress on the tendon in Fig. 5 indicates that the level of Mises stress reaches 100 MPa at the sutured junction. Furthermore, the numerical result shows the Mises stress on the suture and tendon is different. This has been shown in Fig. 6. The stress on the suture is below the failure stress found in the experimental test.

V. Discussion

Our data show that the tendon construct with a suture is stiffer with bigger force induced displacements at different force levels (50, 75, 100 N).

Maximum load to failure did not significantly differ between sutured and unsutured grafts when two tendons are sutured together. But it was different when we only pull the tendon from suture side. In this circumstance, the maximum strength of the structure under loading was lower than the same unsutured tendon and the tendon specimen failed in the sutured region due to cutting by the suture.

The cyclic loading tests confirm the displacement occurring during the first few loading cycles (about five cycles) is significantly different with other cycles. This can be referred to the slippage of the suture over the tendon.

We used tendons with the same mean average diameter and a constant length of the tendon loop as well as the same suture material, it may needs to consider these findings with different suture materials or techniques. Using the whipstitch technique may lead to permanent viscoplastic elongation of the constructs due to slippage of the suture material within the tendon tissue under tensile load. These findings underline the importance of intraoperative graft preconditioning in order to prevent postoperative joint laxity [9].

However, in the cyclic loading test no significant differences in the mechanical properties after preconditioning were found, thus indicating that the mechanical behavior of the sutured and unsutured grafts are comparable, as long as a continuous load is applied to the graft. It is unknown if there are episodes in the early postoperative period with completely unloaded ACL grafts.

There are some limitations that need to be noted. The experimental setup of this study is a simplification of the clinical situation not considering different important clinical factors. Thus, we were able to particularly study the influence of the suturing of a graft on the mechanical properties of the fixation devices.

The numerical modelling predicted the maximum stress at the interface between the suture and tendon. The stress level reaches 100 MPa at the sutured junction under the linear elastic assumption. However, further non-linear analyses and failure mechanisms are needed to achieve a complete understanding on the sutured tendon response under tensile loading.

VI. Conclusion

The study looked at the mechanical effects on a sutured tendon graft applicable to ACL reconstruction under continues and cyclic loading.

The experimental and numerical modeling of the study confirm that there is not significant different between the mechanical property of a sutured tendon for the application of ACL reconstruction as long as continues load is applied to the graft.

References

[1] Fink C, Hoser C, Benedetto KP, Hackl W, Gabl M (1996) Long-term outcome of conservative or surgical therapy of anterior cruciate ligament rupture (in German). Unfallchirurg 99:964–969

[2] Seitz H, Chrysopoulos A, Egkher E, Mousavi M (1994) Long-term results of replacement of the anterior cruciate ligament in comparison with conservative therapy (in German). Chirurg 65:992–998

[3] Wittenberg RH, Oxfort HU, Plafki C (1998) A comparison of conservative and delayed surgical treatment of anterior cruciate ligament ruptures. A matched pair analysis. Int Orthop 22:145–148

[4] Kousa P, Jarvinen TL, Vihavainen M, Kannus P, Jarvinen M (2003a) The fixation strength of six hamstring tendon graft fixation devices in anterior cruciate ligament reconstruction. Part I: femoral site. Am J Sports Med 31:174–181

[5] Kousa P, Jarvinen TL, Vihavainen M, Kannus P, Jarvinen M (2003b) The fixation strength of six hamstring tendon graft fixation devices in anterior cruciate ligament reconstruction. Part II: tibial site. Am J Sports Med 31:182–188

[6] Weiler A, Hoffmann RF, Stahelin AC, Bail HJ, Siepe CJ, Sudkamp NP (1998a) Hamstring tendon fixation using interference screws: a biomechanical study in calf tibial bone. Arthroscopy 14:29–37

[7] Goradia VK, Rochat MC, Grana WA, Egle DM (1998) Strength of ACL reconstructions using semitendinosus tendon grafts. J Okla State Med Assoc 91:275–277

[8] Noyes FR, Butler DL, Grood ES, Zernicke RF, Hefzy MS (1984) Biomechanical analysis of human ligament grafts used in knee-ligament repairs and reconstructions. J Bone Joint Surg Am 66:344–352

[9] Hoher J, Scheffler SU, Withrow JD, Livesay GA, Debski RE, Fu FH, Woo SL (2000) Mechanical behavior of two hamstring graft constructs

for reconstruction of the anterior cruciate ligament. J Orthop Res 18:456–461

[10] Greis PE, Burks RT, Bachus K, Luker MG (2001) The influence of tendon length and fit on the strength of a tendon– bone tunnel complex. A biomechanical and histologic study in the dog. Am J Sports Med 29:493–497

[11] Beynnon BD, Amis AA (1998) In vitro testing protocols for the cruciate ligaments and ligament reconstructions. Knee Surg Sports Traumatol Arthrosc 6:70–76

[12] Hoher J, Livesay GA, Ma CB, Withrow JD, Fu FH, Woo SL (1999) Hamstring graft motion in the femoral bone tunnel when using titanium button/polyester tape fixation. Knee Surg Sports Traumatol Arthrosc 7:215–219

[13] Honl M, Carrero V, Hille E, Schneider E, Morlock MM (2002) Bone-patellar tendon-bone grafts for anterior cruciate ligament reconstruction: an in vitro comparison of mechanical behavior under failure tensile loading and cyclic submaximal tensile loading. Am J Sports Med 30:549–557

[14] Novak PJ, Wexler GM, Williams JS Jr, Bach BR Jr, Bush- Joseph CA (1996) Comparison of screw post fixation and free bone block interference fixation for anterior cruciate ligament soft tissue grafts: biomechanical considerations. Arthroscopy 12:470–473

[15] Robert H, Es-Sayeh J, Heymann D, Passuti N, Eloit S, Vaneenoge E (2003) Hamstring insertion site healing after anterior cruciate ligament reconstruction in patients with symptomatic hardware or repeat rupture: a histologic study in 12 patients. Arthroscopy 19:948–954

[16] Weiler A, Windhagen HJ, Raschke MJ, Laumeyer A, Hoffmann RF (1998b) Biodegradable interference screw fixation exhibits pull-out force and stiffness similar to titanium crews. Am J Sports Med 26:119–126

[17] Becker R, Schroder M, Starke C, Ropke M, Nebelung W (2000) Mechanical properties of suture materials for anchoring cruciate ligament transplants (in German). Unfallchirurg 103:375–379

[18] Chizari M., Wang B., Snow M., 2007, "Experimental and Numerical Analysis of Screw Fixation in Anterior Cruciate Ligament Reconstruction," Proceeding of WCE 2007 (ICSBB'07), London, Vol II, p.1439.

[19] Taylor A.H., Stibbs M., Miles A.W., Webb J., 2002, "The Effect of Tendon Suturing Techniques on ACL Graft Tension," Journal of Bone and Joint Surgery, British Volume, Vol 84-B, Issue SUPP-II, p. 161.

[20] Dietmar Krappinger; Franz Sebastian Kralinger; Rene El Attal; Wolfgang Hackl; Christian Haid; Modified Prusik knot versus whipstitch technique for soft tissue fixation in anterior cruciate ligament reconstruction: a biomechanical analysis Knee Surg Sports Traumatol Arthrosc (2007) 15:418-423