Slippery motion between the limbs of a double tendon graft

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Abstract. Relative motion of tendon limbs of a double tendon graft for the application of anterior cruciate ligament (ACL) reconstruction may affect the mechanical behaviour of a tendon graft structure. The biomechanical data derived from the standard tensile testing machines may not be able to show the relative motion of the graft limbs. This paper uses the non-destructive digital stereo imaging recording system, synchronized with the standard test machine, to precisely determine the biomechanical properties of 10 bovine flexor tendon grafts which hanged from the loop side to the rig and the other end was fixed in a bone block. The study showed there is a relative motion between graft limbs.

Introduction

Accurate measurement of the biomechanical properties of tendons grafts is important, especially for the surgical repair of ACL injuries. Tensile testing has been the most extensively used methods for measuring the properties of tendons. The tendon consists of numerous collagen fibrils, each with very different mechanical properties and the mechanical behaviour of the tendon is complex and difficult to model. The biomechanical data derived from the standard tensile testing machines may not be entirely accurate.

In an effort to develop a more accurate method for measuring the mechanical properties of tendon, the investigation of alternate technologies has led to the use of digital image correlation (DIC) technology.

DIC has been used in experimental studies of stress analysis of materials such as metals, concrete and rubbers and fracture dynamics [1,2,3]. Since then DIC has been used to study the mechanical properties of biological soft tissues e.g. human tympanic membrane [4], sheep bone callus [5], human skin [6], bovine cornea [7] and mouse arterial tissue [8].

The technique utilizes two similarly speckled images, captured by a solid state video camera, to represent the states of an object before and after deformation, yielding a displacement field of the tendon surface. In order to create a characteristic pattern on the specimen surface, black paint is deposited on the surface of the specimen. The testing specimen is then installed onto a loading frame and speckle patterns are acquired at various loading conditions [9]. Combined with simple tensile tests, DIC may precisely determine the soft tissue properties including Young's modulus, breaking strength and ultimate strain.

The aims of this study were to:

1. Validate the use of a DIC system using experimental data from tensile load displacement tests of an ACL model. 2. To examine the mechanical behaviour of a doubled tendon graft in an ACL model.

Material and methods

In this study the in vitro mechanical properties of the 10 bovine digital flexor tendon constructs was determined. Bovine digital flexor tendon was used to represent hamstring tendon graft (Fig 1a). The harvested tendons were cleared of adherent muscle fibers and surrounding soft tissues. The tendons were frozen at -20°C in sealed plastic bags for no longer than three months. These preservation procedures have been shown not to affect the mechanical properties of tendon [10].

On the day of testing, the tendon was thawed to room temperature (for 2-4 hours). All of the specimens were kept moist with normal saline during specimen preparation, and biomechanical testing.

The tendons were cut into 220 mm lengths and both ends were whip-stitched using No.2 Ultrabraid® (Smith & Nephew, Andover, MA) for a distance of 30mm (Fig. 1a).

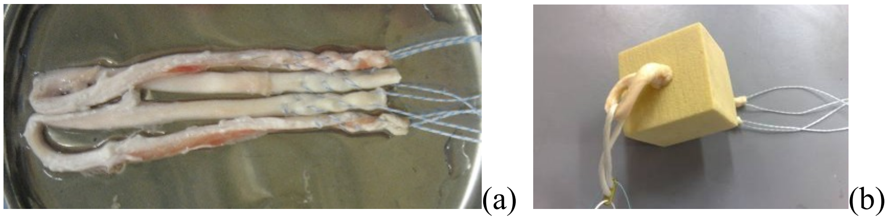
(a) (b)

Fig 1. Ten bovine flexor tendon specimens were prepared for the experimental tests (a); the specimens were fixed with an interference screw into bone block models (b).

Ten synthetic solid foam testing blocks with a density of 0.32g/cc (Pacific Research Laboratories, Malmo, Sweden) were used as a bone model. The foam was cut into blocks measuring 30mm x 45mm x 40mm. All foam blocks were prepared in the same way.

Each tendon was doubled through a 40mm Endobutton (Smith & Nephew, Andover, MA) then the diameter of the tendon was measured using a standard graft measuring block.

A tunnel matching the graft diameter was drilled through the centre of the foam block and the debris was cleaned carefully from the tunnel. The graft was then passed through the tunnel until a 30mm gauge length was achieved. The graft was fixed with a standard metallic interference screw (Arthrex, Naples, FL) with the same diameter as the tunnel (Fig 1b). The Endobutton loop and the sawbone block were secured in custom-made grips in a LOS (Losenhausen, Maschinenbau AG Dusseldorf) testing machine.

Biomechanical testing

The constructs were pre-conditioned by cycling at 1Hz from 10 to 50N for 10 cycles followed by cyclic loading from 50-250N at 1.0Hz for 500 cycles. Following cycling a load to failure test was carried out at a rate of 20mm/min [11, 12]. Failure was defined as tendon rupture or graft slippage. The ultimate tensile stress, yield load, failure strain, stiffness, cyclical elongation and mode of failure was then determined for each specimen.

Silicon carbide and talc particles were spread on the specimen surface just moments before tension was applied, in order to generate high-contrast black-and white speckles. Fig 2 shows the experimental setup, the position of the camera in relation to the tensile machine, and an example of a speckled image created.

Experimental measurements were carried out using a DIC system with two cameras (Limess GmbH, Pforzheim, Germany), and Vic3D software (Correlated Solutions, Inc., South Carolina, USA).

The load was recorded together with the displacement by the DIC system. The software was used to calculate the displacement and strain in the tendon limbs. The displacement data was processed in Vic3D and exported as a text file for further analysis. From these measurements estimations of stress, vertical and shear strain were made.

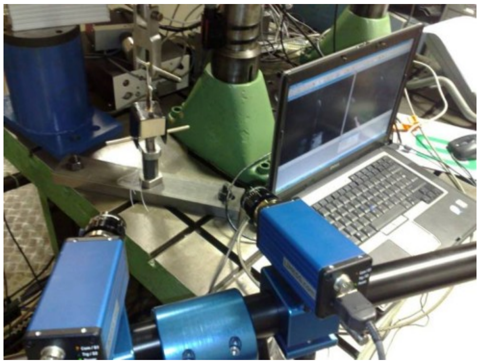

Fig 2. The mounted specimen in a LOS testing machine. DIC technique was used to measure displacement of the markers. Experimental measurements were carried out using a Correlated Solutions system, using two cameras and Vic3D software.

Results

Typical load-displacement result of pre-conditioning, cyclic loading and single cycle load to failure test is demonstrated in Fig 3. The mean cross sectional area of the tendon specimens was 38.48mm^2 and the ultimate tensile stress of the specimens calculated from average data was 10.37 MPa. Table 1 is summarized the mechanical properties of the double tendon graft specimens.

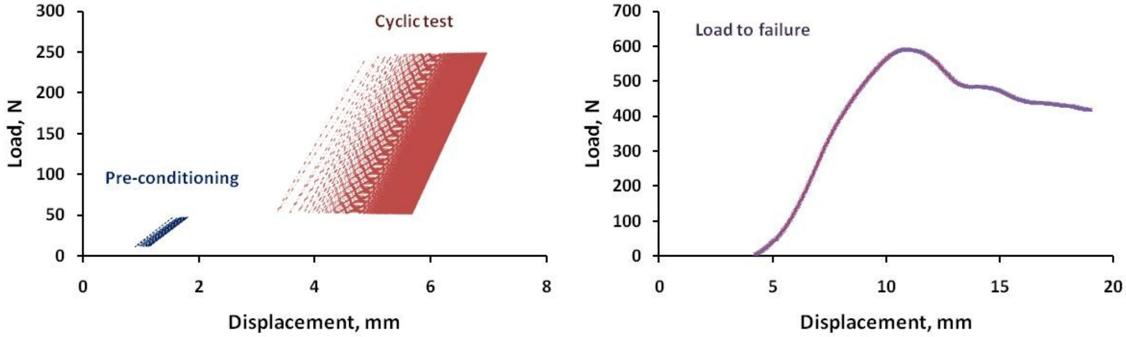

Fig 3. Load-displacement relation of a typical tendon graft under pre-conditioning, cyclic loading and load to failure examination.

Table 1. Mechanical properties of the double tendon grafts. The results represent average values.

	Ultimate tensile strength	Yield load	Failure strain	Stiffness at failure	Failure mode
Double tendon (n=10)	586.7 N (48.8)	592.62 N (58.6)	0.28	65.97 N/mm	fixation

By analyzing any pair of consecutive speckle images with the DIC technique, displacements between the corresponding load levels, incremental displacements can be obtained [13]. Table 2 is reporting the result obtained from mechanical testing machine and DIC analysis.

The average gage length of the grafts before and after pre-conditioning and cyclic test is summarised in Table 3. The results of the two method of measurement show a close agreement.

Table 2. Relative motion between the graft limbs. The results represent average values.

	Graft displacement at pre-conditioning	Graft displacement at cyclic loading	Graft displacement at failure	Relative motion between loop limbs at failure
Double tendon (n=10)	0.36	2.13	8.98 mm	0.3 mm

Table 3. Comparing the result of the testing machine and DIC method after cyclic test (mean value)

Method	Initial gage length	Gage length at yield point	Gage length at failure
Tensile machine	29.1 mm	32.1 mm	36.1 mm
DIC method	29.6 mm	32.8 mm	37.1 mm

With increasing load, the displacement in the 2 limbs of the tendon graft was slightly different. The mean relative motion between the loop limbs was 0.3 mm. The mean total structural displacement of the graft at failure was 8.98 mm, but the discrepancy in displacement of the 2 limbs resulted in differing values of strain for the individual limbs. The average strain for limb1 and limb2 were 0.169 and 0.148 respectively.

At the maximum load before failure the maximum vertical strain was 0.42 and the shear strain was 0.26. Fig 4 presents the contour of vertical strain and shear strain at the stage of maximum tensile loading. The incremental displacement along vertical direction was therefore much more significant than the horizontal direction, caused by Poisson's effect. The sample failed shortly after this section.

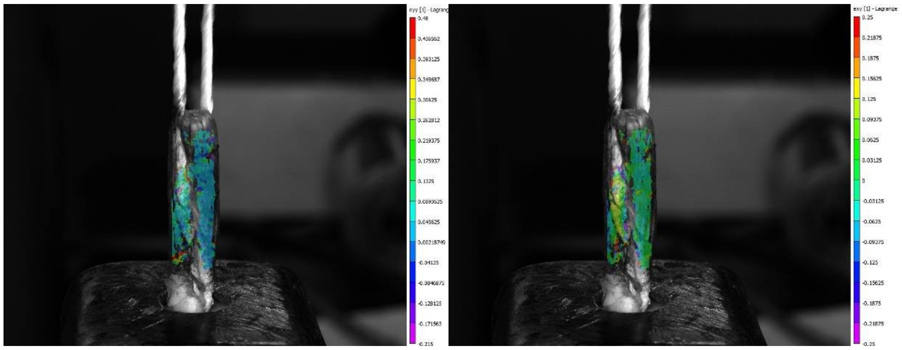

Fig 4. Contour of the strain in vertical direction (left) and shear strain (right) resulted from DIC measurement at the maximum load moment during the tensile loading of the tendon graft.

Discussion

The increased anterior-posterior laxity, slower healing of the tendon graft to the bone tunnel, fixation strength, graft tension, and graft motion within the tunnel leading to enlargement of the tunnel opening are some of the potential problems associated with the use of hamstring tendon grafts in ACL reconstruction [12]. Optimal initial fixation of an ACL graft requires sufficient initial strength to avoid fixation failure, sufficient stiffness to restore stability of the knee, anatomic fixation to minimize graft movement within the tunnel, and sufficient resistance against slippage under cyclic loading conditions to avoid gradual loosening during the early post-operative period after ACL reconstruction [12].

The results have shown that DIC provides a reliable technique for assessing the biomechanical properties of a tendon graft. Our results have validated the use of DIC as compared to the gold standard of tensile loading machines in terms of collecting biomechanical data for tendon properties, as DIC was able to measure displacement in tendon grafts. No statistical significance was found between the mechanical data derived from the 10 tendon specimens using the DIC and standard tensile machine.

The DIC was able to confirm findings of the experimental data whilst additionally providing information on the separate limbs of the tendon graft. With the DIC system, the strain pattern was visible between the 2 limbs of a doubled graft when used in association with suspensory fixation. This relative motion between the two limbs may be due to unequal fixation force for both strands in the tunnel, non-uniform graft slippage or cut tendon fibres under loading.

There are a number of weaknesses in our study. The DIC was able to characterise the superficial properties of the tendon surface. But the underlying bulk constitutive properties of tendons undergoing large deformations were not determined. Moerman et al. [14], were able to use DIC technology combined with finite element modelling to determine the underlying bulk properties of tissues in vivo.

A continuous-loop Endobutton and metallic interference screw were used in our study. These methods have been commonly used for the fixation of hamstring tendon grafts [15]. Hence the observations noted concerning the difference in limb motion and unequal strain may be true with these methods of fixation. We cannot comment if this is true for other methods of fixation as the design of the interference screw may have an effect on graft slippage of soft tissue fixation under cyclic loading conditions e.g. the tendon graft may be damaged by the sharpness of the screw thread itself [12].

Even though the model needs further experimental work, we have validated the use of DIC as compared to the gold standard of tensile loading machines in terms of collecting biomechanical data for tendon properties, as DIC was able to measure displacement in tendon grafts. And this does not limit the clinical application of the study.

DIC has great potential for helping us understand the stresses involved in ACL reconstruction. This initial model needs further development, but in the future may help us to understand reasons for tendon graft failure in ACL repair and hence maximise success.

DIC, in turn may help clinicians to more accurately determine the mechanical properties of tendon constructs used in surgical reconstruction and subsequently improve fixation, e.g. the differing properties between a doubled and tripled tendon graft used for anatomical ACL reconstruction.

Conclusion

In this study we have validated the use of a DIC system using experimental data from tensile load displacement tests of an ACL model and examined the mechanical behaviour of a doubled tendon graft in an ACL model. Relative motion of a double tendon graft applicable in ACL reconstruction was assessed and we showed that there is a relative motion between the graft limbs. DIC has great potential for helping us understand the stresses involved in ACL reconstruction. This initial model needs further development, but in the future may help us to understand reasons for tendon graft failure in ACL repair and hence maximise success.

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References

[1] Chao Y.J., Luo P.F., An experimental study of the deformation fields around a propagating crack tip. Exp Mech 1998, 38: 79-85.

[2] Choi S., Shah S.P., Measurement of deformations on concrete subjected to compression using image correlation. Exp Mech 1997, 37: 307-313.

[3] Sutton M.A., Chae T.L., Development of a computer vision methodology for the analysis of surface deformations in magnified images; in George F. (ed): MicCon 90, Advances in Video Technology for Microstructural Control, ASTM STP 1094. Philadelphia, American Society for Testing and Materials, 1990.

[4] Cheng, T., Dai, C., Gan, R., Viscoelastic properties of human tympanic membrane. Annals of Biomedical Engineering, 2007, 35(2): 305-314.

[5] Thompson, M.S., Schell, H., Lienau, J., Duda, G.N., Digital image correlation: a technique for determining local mechanical conditions within early bone callus. Medical Engineering and Physics, 2007, 29(7); 820-823.

[6] Mahmud J. "The Development of a Novel Technique in Measuring Human Skin Deformation *in vivo* to Determine its Mechanical Properties". 2009 PhD Thesis, Cardiff University, UK.

[7] Boyce, B.L., Grazier, J.M., Jones, R.E., Nguyen, T.D., Full-field deformation of bovine cornea under constrained inflation conditions. Biomaterials, 2008, 29(28): 3896-3904.

[8] Sutton, M.A., Ke, X., Lessner, S.M., Goldbach, M., Yost, M., Zhao, F., Schreier, H.W., Strain field measurements on mouse carotid arteries using microscopic three-dimensional digital image correlation. Journal of Biomedical Materials Research Part A, 2008, 84A(1): 178-190.

[9] Hung P.C., Voloshin A.S., In-plane strain measurement by digital image correlation. Journal of the Brazilian Society of Mechanical Sciences and Engineering, 2003, 25(3): 215-221.

[10] Beynnon B.D., Amis A.A., In vitro testing protocols for the cruciate ligaments and ligament reconstructions. Knee Surg. Sports Traumatol Arthrosc. 1998, 6(1): S70-S76.

[11] Zantop T., Weimann A., Wolle K. et al, Initial and 6 weeks postoperative structural properties of soft tissue anterior cruciate ligament reconstructions with cross-pin or interference screw fixation: an in vivo study in sheep. Arthroscopy, 2007, 23(1):14-20.

[12] Kousa P., Järvinen T.L.N., Vihavainen M., et al, The fixation strength of six different hamstring graft fixation devices in anterior cruciate ligament reconstruction. Part I, Femoral site. Am. J. Sports Med, 2003, 31: 174-181.

[13] Snow M., Cheung W., Mahmud J., Evans S.L., Holt C.A., Wang B. and Chizari M. Mechanical assessment of two different methods of tripling hamstring tendons when using suspensory fixation. Knee Surgery, Sports Traumatology, Arthroscopy, 2012, 20(2): 262–267.

[14] Moerman K.M., Holt C.A., Evans SL, Simms CK. Digital image correlation and finite element modelling as a method to determine mechanical properties of human soft tissue in vivo. Journal of Biomechanics, 2009, 42: 1150-1153.

[15] Brown C.H. and Sklar J.H., Endoscopic anterior cruciate ligament reconstruction using doubled gracilis and semitendinosus tendons and endobutton femoral fixation. Arthroscopy: The Journal of Arthroscopic and Related Surgery, 1999, 7(4): 201-213.