Mechanical Aspects of an Interference Screw Placement in ACL Reconstruction

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Abstract. The physical status of an interference screw fixation in an anterior cruciate ligament (ACL) reconstructive surgery is a crucial factor of success. In this study, the insertion of the interference screw into a tibial bone tunnel, and the advancement of the screw between the tendon strands were investigated using both experimental and computer modeling. The mechanical behavior of the bone and soft tissue during the screw insertion, and the effect of the misalignment of the screw in the bone tunnel were investigated. Both concentric and eccentric placements of the screw were closely monitored and the results of both cases were compared.

1 Introduction

Precise positioning of an interference screw and the alignment of the graft fixation into the tibial tunnel is a critical step in ACL reconstruction. Nowadays, most surgical reconstructions are free of complexity, however many aspects of ACL reconstructions still need to be better examined and understood [1]. The interference screw fixation is routinely used for hamstring ACL reconstruction, but the problem of postoperative bone tunnel mechanical instability still exists with this type of fixation [2]. One of these aspects is represented by the post-operative tunnel enlargement, which takes place in many patients following ACL reconstruction [2]. Even though many studies have shown that this issues usually does not have any sort of short to midterm clinical relevance, it could represent a serious concern in the case of revision surgery. Many authors have hypothesized that the aetiology of tunnel enlargement could be multifactorial, and instigated due to both mechanical and biological factors [2]. However, the post-operative bone tunnel enlargement has consistently led to revision ACL surgery [3], possibly due to bone stress deprivation around the tunnels [4]. The bone damage can be caused by repetitive compression from soft tissue graft anchors (e.g. interference screw) leading to an accumulation of micro damage [5] and eventual bone fracture at the button fixation site.

The objective of this study is to achieve a better understanding of the mechanics of a common interference screw fixation in the tendon graft reconstruction of the ACL. The study aims to investigate the status of the interference screw following the insertion into the tibial bone tunnel, using both experimental and numerical methods.

2 Material and Methods

2.1 Experimental simulation

An experimental evaluation was setup to investigate the effects of the misalignment of the interference screw in the fixation of the tendon graft into a tibial tunnel. Porcine tibia bone and bovine digital flexor tendon was used to represent the bone model and tendon graft. The harvesting procedure and the biomechanical tests were based on clinical and ethical protocols. The harvested bones and tendons were cleared of adherent muscle fibers and surrounding soft tissues. The specimen was kept moist with water during the specimen preparation, fixation procedures, and biomechanical testing.

The tendons were whipstitched at their free ends for 25 mm with No. 2 vicryl. Two 160 mm long tendons were doubled to construct a four-strand tendon graft with a total graft length of 80 mm. The total diameter of the graft was then measured using sizing tubes. The tendon grafts with diameters passage into a 10 mm bone tunnel (same size or 0.5mm less than the tunnel diameter) were identified and used for the experiment.

The tibial tunnel was created by initially inserting a guide pin within the ACL footprint of the tibia using a standard tibial aimer set at 50 degrees. A cannulated drill was used to create a tunnel with a 10 mm diameter. The looped end of the tendon graft was pulled through the tunnel with the aid of the passing suture and hooked to a rig. The tendon graft was pulled through the bone tunnel until 30 mm of graft protruded from the proximal opening of the bone tunnel. After this stage, the four-tailed ends of the graft strands were holed equally around the tunnel, and a 10 mm interference screw was subsequently inserted concentrically between the tendon strands.

Positioning the screw into the tunnel and advancing it between the tendon strands was the next stage of the fixation. Ideally, the screw should sit between the tendon strands and be aligned with the center of the tunnel. However, in practice, lateral movement of the screw pushes the tendon strands away from the axis of the tunnel and moves them in the circumstantial direction, so that they become un-symmetrically arranged. Fig. 1a shows the non-symmetric final position of the strands.

With the screw positioned concentrically, the screw is only in contact with the tendon graft. However, the lateral movement of the screw inside the tunnel causes an eccentric position and with this situation, the screw would have contact with both the tendon and the bone.

In some specimens, it was monitored that the screw pushed the tendon aside circumferentially (Fig. 1a) and cut directly into the bone (Fig. 1b).

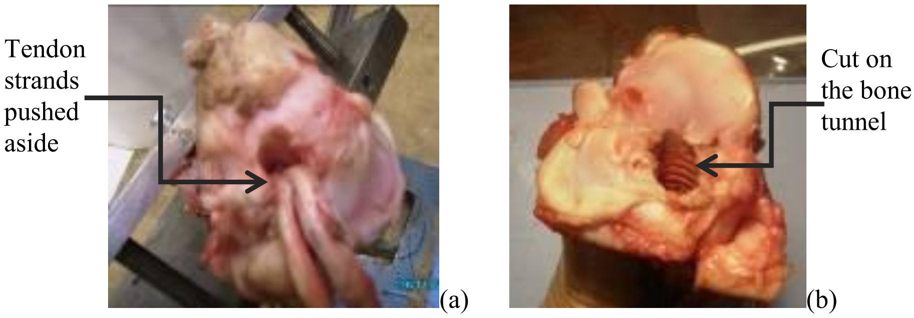


Fig. 1. A porcine tibial bone sample following a pull-out test. The tendon graft was pushed aside of the tunnel (a) and the screw cut the bone (b)

2.2. Computer modelling

A finite element computer method was used to model the mechanical behaviour of the bone and soft tissue biomechanics of the ACL reconstructed knee, in particular on reconstructions which use interference screws for a tendon graft fixation. Abaqus 6.11 (Simulia Dassault Systems) finite element software with an explicit post-processing solver was used to perform the following tasks:

- To simulate the interference screw being driven into a tibial tunnel.
- To model the bone and tendon graft deformation during the insertion.

Dynamic or static loads were applied to the model to mimics the mechanical behaviour of the knee during and after the ACL reconstruction. The dynamic simulation of the advancing screw was examining the problem at the screw insertion stage. The aim was to monitor the level of stress during the implanting the device until the device is fully inserted into the bone tunnel. After this stage the static model was applied. The stress analysis of the fixation under static loading would simulate the knee at the rest condition and thereby only internal forces were determined. The two following models were considered for further evaluation:

- Simulation of the interference screw insertion into a bone tunnel in the absence of the tendon graft. This simulation aims to model direct contact of the interference screw with the bone tunnel.
- Evaluating the screw advancement between the tendon strands in the tunnel which simulate the contact behavior of the screw and soft tissue tendon graft in the bone tunnel.

2.2.1. Modeling of an screw insertion into a bone tunnel

The 3D model of the interference screw fixation into the tibial bone was created based on the active thickness of the bone around the tunnel. To simplify the model, a section of the tibial bone tunnel was created (Fig 2). The model was a cylinder with overall diameter of 30 mm and a 10 mm hole inside. Also a 10 mm diameter screw was modeled to be inserted into the bone tunnel (Fig. 2b). The length of the tunnel was set to 30 mm corresponding to the length of the screw.

The bone was modeled using 3-dimensional C3D4 solid element, which is a 4-node linear tetrahedron element provided by the software. Reduced integration and hourglass control was applied. The screw was modeled using R3D4 elements which are 4-node 3-dimentional bilinear rigid quadrilaterals [6].

Contact pairs were defined between the screw and tunnel. Node-based surfaces were defined as containing nodes on the outer surfaces of solid elements. The use of a node-based surface implies a pure master-slave relationship for the contact pair. A non-reflective boundary condition was assumed for the tibial tunnel.

The stress in the bone at the interface with the screw was examined at different stages of fixation. The screw was loaded with a force of 200 N (corresponding to the force which can be applied by hand during the screw insertion) directed along the tunnel axis and a rotational movement which was calculated based on the screw's pitch. The screw was inserted into the tunnel by combined axial speed of 1.5 mm/s, and rotational speed of 1.0 round per second (360^o/s) [3].

Fig. 2b shows an advancing interference screw into the tibial tunnel. The stress on the bone tunnel varies between 6-14 MPa. The maximum stress occurs in the interface between threads of the screw and bone while the lowest stress is in the distal end of the tunnel. The bone material may fail in the vicinity of the screw threads as the stress is higher than the yield point of the bone in this region [7].

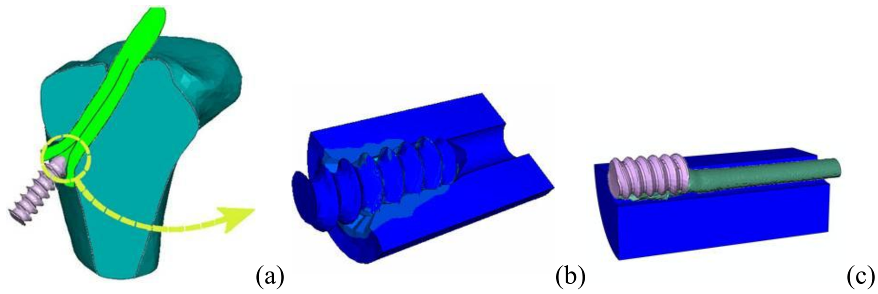


Fig. 2. Schematic view of a tibial bone (a) and selected section of the bone around tunnel while a screw advancing into it (b) advancing screw on a tendon strands inside the tunnel (c)

2.2.2. Modeling of an advancing screw on a tendon strand

A numerical simulation was performed to analyse the contact behaviour at the interface between the screw and tendon graft, while the screw is advancing on the tendon strands. It was assumed that the screw should ideally sit symmetrically between the four strands of the tendon graft.

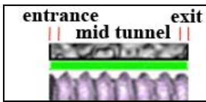
The model was created only for a section of tibial bone containing a cylindrical tunnel, with a 10 mm hole inside and an overall diameter of 30 mm. The length of the tunnel was corresponding to the length of the screw (30 mm). A 10 mm diameter screw was also modeled to be inserted into the tunnel. A four-strand tendon, with strands of 3.5 mm in diameter, was uniformly assembled and tied to the tunnel (Fig.

2c). To simplify the model only a quarter of the tibial bone with a tendon strand was considered. The tendon strand was pre-loaded at 100 N in axial direction. Obviously, the graft force may vary with the knee activities, but the aim of this model is to focus on the deformation of the tendon graft during the screw fixation, rather than the strength of the fixation, therefore a constant axial force was applied to the tendon.

Based on the literatures, the friction coefficients between the tendon-bone, screw-tendon and screw-bone were assumed 0.25, 0.3 and 0.37 respectively [3]. A penalty contact surface with the appropriate friction was defined between the screw, tendon and bone. To simplify the model, the screw was modelled as a uniform cylindrical shape. As shown in Fig. 2c, by advancing the screw on the tendon strand a large deformation of the tendon strand was occurred. The stress and displacement of the tendon and bone at the contact zone was evaluated and the results are summarized in Table 1.

The stress reaches approximately 10 MPa for the tendon graft and about 4 MPa for the tibial bone. Table 1 also indicates a large deformation of up to 2.7 mm in diameter in the tendon but only 0.5 mm in the bone tunnel. This means there is 1 mm enlargement in the tunnel diameter after screw insertion. During screw insertion the tendon deforms and fills the gap between the screw threads.

Table 1. Results obtained from the finite element modelling of a 30 mm bone tunnel, when a 30 mm interference screw is fully inserted into the tunnel.

		**Entrance**		**Mid tunnel**		**Exit**	
		Average	Max	Average	Max	Average	Max
Mises Stress, MPa	Bone	1.5	1.8	2.2	4.0	1.0	1.8
	Tendon	2.5	3.1	7.8	10.1	3.8	5.8
Displacement, mm	Bone	0.20	0.23	0.32	0.46	0.26	0.28
	Tendon	0.75	0.78	1.75	2.2	2.32	2.77

2.2.3. Simulating the concentric and eccentric placement

The location of the graft limbs inside the bone tunnel is an important factor in determining a good graft fixation. A non-isometric placement of the graft cannot be compensated by other factors, such as rigid fixation or proper pre-tensioning on each tendon strands [6]. Fig. 3 shows possible positions of the screw and tendon into the bone tunnel. With the screw positioned concentrically (Fig. 3a), the screw only has an interface with the tendon graft, but in the eccentric situation (Fig. 3b), the screw has direct contact with both tendon and bone.

The result of a stress analysis of the concentric placement when the screw is fully inserted into the bone tunnel is shown in Fig. 4. The result was obtained for opposite sides of the bone tunnel (sides A and B as indicated in the figure), where the stress was a maximum or a minimum. The figure shows that with the concentric position of the screw into the tunnel, the stress on different sides of the bone tunnel is almost the same. Hence, with this concentric placement, the interference screw surrounded by the tendon material and there is no direct contact between the interference screw and bone.

Possible eccentric positions when the screw is fully inserted into the tunnel are shown in Fig. 5. A full or partial contact may occur between the screw, bone and tendon in eccentric placement. As shown in Fig. 5a, with the eccentric placement the level of stress on the bone side (side A) is higher than the tendon side (side B). But the level of stress when the screw has a partial contact with the bone and tendon is maximum when the screw has direct connection with the bone and minimum when the screw has contact with the tendon. In this case the stress along the tunnel is not uniformly distributed as shown in Fig. 5b.

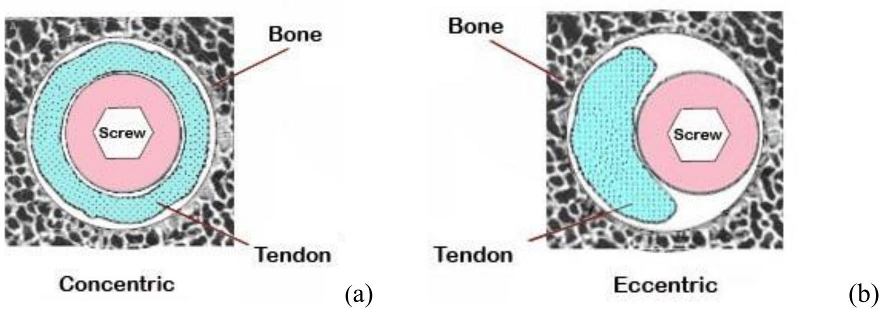


Fig. 3. Schematics of the possible placement of the screw in the bone tunnel. The concentric placement (screw is in the middle and surrounded by the tendon graft) (a), and eccentric placement (screw is off the center and sited between the bone and tendon graft) (b)

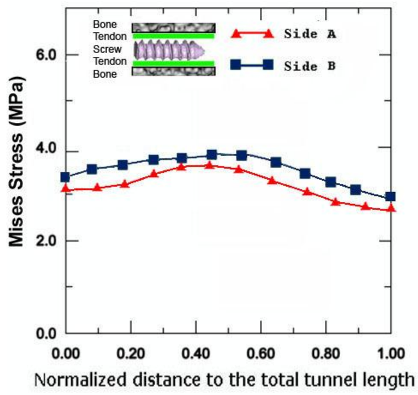


Fig. 4. Mises stress on the tibial bone tunnel when the screw is concentrically positioned inside the tunnel (screw is surrounded by the tendon and there is no direct contact between the screw and bone)

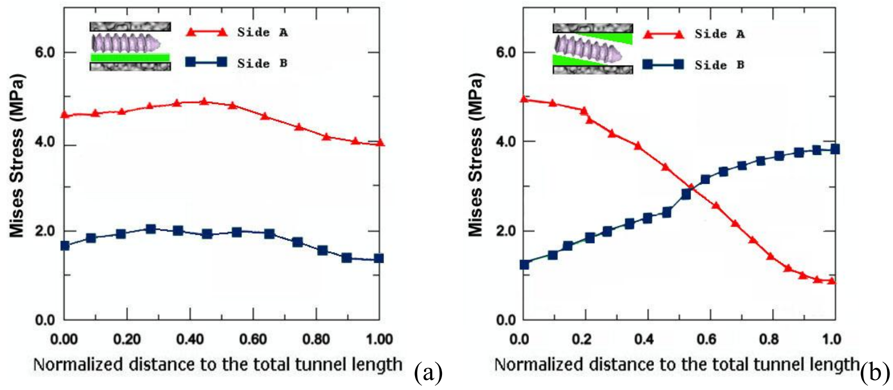


Fig. 5. Mises stress on the tibial bone tunnel, with the screw eccentrically positioned into the tunnel. Possible eccentric positions are; the tendon moves aside and the screw becomes in full contact with both tendon and bone (a), or the screw only has partial contact with the bone and tendon, as the tendon is aside but twists along the tunnel (b)

3. Conclusion

This study presented an experimental and numerical investigation on the bone and tendon graft biomechanics of an ACL reconstructed knee, in particular on reconstructions which use interference screws for tendon graft fixation. The study focused on the insertion of the interference screw into the tunnel and its possible placement between the tendon strands.

The experimental investigation of this work showed that by inserting an interference screw between the tendon strands the screw may push the tendons laterally and cut the bone. It was shown the lateral movement of the screw inside the tunnel causes an eccentric position and with this situation, the screw would be in contact with both the tendon and the bone.

To investigate the effect of an interference screw fixation on the bone and tendon, the study used a model created only for a section of tibial bone in the region of the tunnel. The model was evaluating the stress on the tendon and bone at the interface with the screw during fixation. In the absence of the tendon graft, the stress on the bone tunnel varies between 6-14 MPa. The maximum stress occurs in the interface between threads of the screw and the bone tunnel and the lowest stress is in the distal end of the tunnel.

The FE modelling of a tendon graft screw fixation shows the stress reaches about 10 MPa for the tendon graft and 4 MPa for the tibial bone. It also shows a large deformation up to 2.7 mm in diameter in the tendon but only 0.5 mm in the bone tunnel.

A concentric placement of the screw into the bone tunnel results in a uniform stress distribution on the tendon and bone. With the eccentric placement, the screw may become partially in contact with the bone and tendon. In this case, the stress on the tendon and bone along the tunnel may vary.

The current numerical modeling assumes that the mechanical properties of the bone and tendon are linear elastic, isotropic and homogeneous. Neither yield nor failure was introduced into the modeling.

References

1 Robinson, J., Huber, C., Jaraj, P., Colombet, P., Allard, M., Meyer, P.: Reduced bone tunnel enlargement post hamstring ACL reconstruction with poly-l-lactic acid/ hydroxyapatite bioabsorbable screws. The Knee. 13 (2006) 127-131

2 Iorio, R., Vadala, A., Di Vavo, I., De Carli, A., Conteduca, F., Argento, G., Ferretti, A.: Tunnel enlargement after anterior cruciate ligament reconstruction in patients with post-operative septic arthritis. Knee Surg Sports Traumatol Arthrosc. 16 (2008) 921-927

3 Chizari, M., Wang, B., Snow, M., Barrett, M.: Experimental and numerical analysis of screw fixation in anterior cruciate ligament reconstruction. AIP Conf Proc 1045 (2008) 61-70

4 Chizari, M., Wang, B., Snow, M.: Experimental and numerical analysis of screw fixation in anterior cruciate ligament reconstruction. Proceedings of the World Congress on Engineering 2007. Vol II p1439-1442 London (2007)

5 Chizari, M., Wang, B., Snow, M.: Post-operative assessment of an implant fixation in anterior cruciate ligament reconstructive surgery. Journal of Medical Systems. 35 (5) (2011) 941-947

6 Chizari, M., Wang, B., Barrett, M., Snow, M.: Mechanical aspects of a single-bundle tibial interference screw fixation in a tendon graft ACL reconstruction. Biomedical Engineering: Applications Basis and Communications. 22 (4) (2010) 271-278

7 Chizari, M., Wang, B., Barrett, M., Snow, M.: Biomechanical testing procedures in tendon graft reconstructive ACL surgery. Biomedical Engineering: Applications Basis and Communications. 22 (5) (2010) 427-436