Contact pressure on ACL hamstring grafts in the bone tunnel with interference screw fixation — Dynamic adaptation under load

Meyer, D C; Stalder, Michael; Koch, Peter P; Snedeker, Jess G; Farshad, Mazda

Abstract: INTRODUCTION: Interference screws used in fixation of anterior cruciate ligament (ACL) hamstring grafts create mechanical hold by forcing the graft into frictional contact with the bone tunnel. We analyzed the resultant graft-tunnel contact pressure using an in vitro model of human cadaver 8mm hamstring grafts. METHODS: Contact characteristics were assessed using both pressure sensitive films and a force sensor. Two screw sizes were investigated (8 and 9 mm in an 8mm Sawbone tunnel), both with and without a bone wedge between graft and screw. Separately, time dependent relaxation of contact force was recorded over a one hour epoch and associated tendon water loss was measured. Pullout testing of 8mm tendon grafts from 8mm holes in Sawbone and porcine femora were performed after 1 min and 1h. RESULTS: During screw insertion, measured peak pressures (>40 MPa) exceeded the compressive failure stress of metaphyseal bone by more than an order of magnitude. Using a bone wedge between tendon and screw reduced local peak pressure by 85% but produced also inferior average contact pressure. In all approaches, initially achieved graft contact pressure rapidly decreased to approximately 25% within 30 min. Pullout strength was significantly reduced after 1h in comparison to 1 min in porcine bone as well as Sawbone. CONCLUSION: Viscoelastic adaptation of the tendon is severe and critically reduces effective graft-bone contact pressure. Consideration of this newly recognized effect may open new and improved approaches for tendon graft fixation.

DOI: https://doi.org/10.1016/j.knee.2011.11.005

Posted at the Zurich Open Repository and Archive, University of Zurich
ZORA URL: https://doi.org/10.5167/uzh-66257
Submitted Version

Originally published at:
DOI: https://doi.org/10.1016/j.knee.2011.11.005
Title: Contact pressure on ACL hamstring grafts in the bone tunnel with interference screw fixation - dynamic adaptation under load

Article Type: Original Article

Keywords: Contact pressure; ACL hamstring graft; interference screw

Abstract: Introduction: Interference screws used in fixation of anterior cruciate ligament (ACL) hamstring grafts create mechanical hold by forcing the graft into frictional contact with the bone tunnel. We analyzed the resultant graft-tunnel contact pressure using an in vitro model.

Methods: Contact characteristics were assessed using both pressure sensitive films and a force sensor. Two screw sizes were investigated (8 and 9 mm in an 8mm sawbone tunnel), both with and without a bone wedge between tendon and screw. Separately, time dependent relaxation of contact force was recorded over a one hour epoch and associated tendon water loss was measured. Pullout testing of 8mm tendon grafts from 8mm holes in Sawbone and porcine femora were performed after 1 minute and 1 hour.

Results: During screw insertion, measured peak pressures (>40 MPa) exceeded the compressive failure stress of metaphyseal bone by more than an order of magnitude. Using a bone wedge between tendon and screw reduced local peak pressure five-fold but produced also inferior average contact pressure. In all approaches, initially achieved graft contact pressure rapidly decreased to approximately 25% within 30 minutes. A corresponding drop in graft weight of 20-30% was attributed to tendon water loss. Pullout strength was significantly reduced after 1 hour in comparison to 1 minute in porcine bone as well as Sawbone.

Conclusion: Viscoelastic adaptation of the tendon is severe and critically reduces effective graft-bone contact pressure. Consideration of this new effect may open new and improved approaches for tendon graft fixation.
“Contact pressure on ACL hamstring grafts in the bone tunnel with interference screw fixation - dynamic adaptation under load”,
authored by
Dominik C Meyer, MD; Michael Stalder, MD; Peter P Koch, MD; Jess G. Snedeker, PhD; Mazda Farshad, MD, MPH

Ms. Ref. No.: THEKNE-D-11-00147

Note from the authors:

The authors thank the editor and reviewer for their thorough review of our manuscript and the opportunity to revise the text. We have directly addressed the reviewer’s comments on a point-by-point basis (enumerated below) and hope to meet their expectations. Thank you again for investing your time in considering our work.

Author Response to Reviewer 1

General Comment 1: I found this difficult to follow and understand as a result I am sure of my ignorance of all things biomechanical. The main conclusion relates to the effect of water loss. I am not sure if we can draw any conclusions from non-living tissue? I would suggest a biomechanical opinion. To be pragmatic, there are now many large scale and long-term reviews of hamstring anterior cruciate ligament reconstruction and although failures do occur they are very rarely if ever due to failure of interference screw fixation. From a clinical point of view I do not think that this is strong enough to be accepted.

Author response:
The reviewer raises the question about the severity of the clinical problem we address in this manuscript. In our opinion, the problem is twofold and most likely far more important than obvious at first sight. First, interference screw-fixated hamstring grafts often do not tend to fail at once, meaning with an obvious tear with consequent instability. In an unknown percentage of cases (most likely close to 100%) the tendon slips to some degree past the screw in a slow, continuous, subacute manner. The consequence is a reconstruction with an ultimately stable stop in Lachmann testing after healing, but with increased excursion. In the literature, there is a good consensus that operated knees will not have the exact same excursion as the healthy side. Second, tunnel widening has been reported in up to 72% of the patients [1-7] and has been associated with altered biomechanics and long-term failure of the transplant[8-11] by some critical investigators. Regarding the viscoelastic dynamic behaviour of the volume of the graft, it may well be speculated that the effect of tunnel widening is related to the observed effects.
However, the goal of interference screw fixation is mechanical fixation of the graft and we believe that in the light of the very high frequency it is used, it is reasonable to seek for possibilities to further optimize this procedure.
To answer about the methods used in this work, we feel that the used grafts do quite well represent the intraoperative situation, as a tendon graft after harvest is devascularized and may therefore also be seen as “dead” (even though still with living cells, we agree). Regarding the biomechanical behaviour, we are therefore positive that our model does reasonably represent the practical situation in the OR. We agree, that in-vivo data would be very interesting to have to see how different interface pressures affect the survival of the graft tissue. However, such a question was not meant to be answered here and is in fact subject of our current research projects.

The main strength of this manuscript in our eyes is however not only the above-explained clinical and biomechanical relevance, but also the information that can be gathered for development of new approaches for fixation with potential of better outcomes (as also the reviewer 2 has recognized in his general comment below). It seems plausible, that the viscous phase of the here described viscoelastic behaviour of the graft can be eliminated by preconditioning of the graft by mechanical compression of the same before implantation (subject of our current research).

Author Response to Reviewer 2

General Comment of reviewer 2: This is a series of tests of interference screw (IS) fixation, into blind tunnels in porcine bones or else blocks of sawbones foam. It was found that the ultimate tensile holding strength reduced greatly after one hour. This was stated to be due to creep of the tendon graft. Another aspect of the work was to measure the pressure around the IS during insertion, using pressure-sensitive films placed in the tunnel; this accompanied measurements of overall force exerted on the wall of the tunnel. It was shown that insertion of a sliver of bone, to protect the graft from the IS threads, led to reduced graft/bone interface pressures. Mixed feelings. The loss of fixation strength with time after IS insertion is an important finding: grafts could be flattened to pre-empt this effect, while experimenters must control their time to testing protocol.

Author response: Thank you for your interest in the topic. We are glad, that you acknowledge the potential value of the manuscript, meaning that it offers a basis for development of new and improved approaches for hamstring graft fixation. As a matter of fact, it seems plausible, that the viscous phase of the here described viscoelastic behaviour of the graft can be eliminated by preconditioning of the graft by mechanical compression of the same before implantation. This is subject of our current research projects. Graft compression before implantation does also allow reducing the size of the graft and therefore the needed drilling size of the bone tunnel with therefore less bone loss and tighter fit. However, in the here submitted manuscript, the main focus is directed on the biomechanical details of the status quo of the currently used techniques, which appears to be the important basis for all related further research projects.
Specific points of reviewer 2:

1. The paper mentions graft water and weight loss (e.g. abstract line 41), but no description of this measurement in Method and no Results either. So this must be added.

   Author response: Graft water loss and therefore logically also weight loss was clearly observed in the here used serial of experiments. We were however not able to quantify this effect here and did therefore remove any statement in this regard or replaced it with the objective observation of the viscoelastic behavior.

2. Abstract line 42: define graft type and diameter

   Author response: We have modified the last sentence of the introduction in the abstract to provide this information as follows: “We analyzed the resultant graft-tunnel contact pressure using an in vitro model of human cadaver 8mm hamstring grafts.” Thank you.

3. Abstract line 39: this was an 80% loss, not a ‘five-fold reduction’!

   Author response: The peak pressure using a 8mm screw in the setting the normal technique was 26.67Mpa and in the setting of the bone wedge interposition 3.96 Mpa (figure 3a). As proposed we indicate this now as a 85% loss. We have adjusted the sentence in the manuscript according to your suggestion. Thank you.

4. The conclusion is correct and important

   Author response: Thank you for the appreciation.

5. Introduction: concise and adequate

   Author response: Thank you for the appreciation.

6. Method: line 84: define number of graft stands

   Author response: Done as suggest. Thank you.

   Line 85: quote Hull and Howell's paper here


**Line 97: define which face of the foam block had the screw hole.**

**Author response:** As stated “...a hole with a diameter of 8 mm and a depth of 2.75 cm was drilled into the center of the sawbones starting from the laminated (cortical) side.”

**Line 99: re-draw figure 1 to show clearly where the pressure sensitive film was placed.**

**Author response:** Done as suggested.

**Line 116: define screw material.**

**Author response:** Done as suggested. The material is polylactic acid (PLDLAA)

**Line 131: place to add details of graft weighing method.**

**Author response:** See please answer to your specific comment 1.

**Lines 144, 145, 153, 154: must use consistent nomenclature: figure 3 says normal and hybrid, where text says direct and indirect.**

**Author response:** Done as suggested (we have replaced “normal” and “hybrid” in the figure by terms “direct” and “indirect”). Thank you.

**Lines 167-9: must show clearly the origin of the force values, which are not obvious from the graphs of results.**
Author response: Done as suggested

Line 177: add weight loss results.

Author response: See please answer to your specific comment 1.

Discussion:

Although Fig 5 shows that 80% of the clamping force was lost over 1 hour, Fig 6 shows that only 20% of the holding strength was lost. This is an important difference which should be discussed.

Author response: We agree. While the loss in expansion force is more pronounced, it seems this loss is not linearly related to the fixation strength. This has been added to the discussion. Thank you.

Line 201: it was not 80% of the initial contact pressure which was lost, but 80% of the clamping force on the bone block.

Author response: We agree. We have changed the sentence to: “while the initial mechanical purchase at the graft-bone interface may be adequate, we have demonstrated here that within 30 minutes the system loses up to 80% of the initial expansion force due to a viscoelastic behavior.”

Line 210: the pullout strength results are shown in Fig 6. This does not include results for the indirect bone wedge fixation, so either this sentence should be removed, or else the data added to support the sentence.

Author response: True. The sentence has been removed.

Line 219: at present, there is no evidence in the paper to show that any water loss occurred, so either delete sentence or add data.

Author response: True. The sentence has been removed.

Line 224: a good, and important, final sentence.

Author response: Thank you.

Fig 3: I cannot understand this. The caption must be expanded and linked to the clarified new version of Fig 1, so that the reader knows exactly what is meant by 'bone side' and 'screw side' and normal and hybrid.

Author response: Thank you. Done as suggested.
Final comment:

There is a problem with the 'peak pressure' results and related conclusions. Fig 3 shows very much lower pressures for hybrid than normal fixation. The problem is that the pressure sensitive film used is very sensitive to transverse shearing effects, and is liable to give over-readings. This may well have occurred when used against an IS. The film would have been protected from this by the interposed bone chip in the hybrid fixation. Thus, these results likely to be artefactual. I'd suggest deleting this data completely, leaving the clamping force data in place. The paper would still make the more important point about loss of graft fixation due to creep relaxation. Fig 3 shows bone pressures of approx 40MPa - this is 10x higher than could be sustained by cancellous bone, so it is either artefactual or else from a local 'hot spot' on the cortical shell, rather than the rest of the IS in the tunnel.

Author response: Thank you for this important input. While such an artificial phenomenon might indeed have influenced the pressure films at the screw side, it can hardly have affected the films at the bone side (see figure 1) during screw insertion. The indirect fixation method (Figure 3) showed also a massive lower peak pressure on the unbiased bone side, which supports your concern. However, the relative proportions are likely to be correctly represented and even though shearing may indeed be present, the films were well “greased” with fat and water from the tendon and furthermore protected with the protective film. Further, when we compare the measured peak pressure with the breaking strength of cancellous bone or sawbone to get an idea of the range we are in, the found values seem not to be far off. Therefore we believe that the qualitative statement of the data is still correct with the according limitations. We therefore propose that this should be discussed but rather not deleted from the manuscript. Therefore we have added this valuable aspect to the discussion. Thank you.

Author Response to the Editor

Editor’s comment: Thank you for your submission. As you can see from reviewer 1’s comments, this paper is indigestible to the ordinary reader. Reviewer 2 has given cogent criticisms which you should address. If you choose to send back a revised version, it must be comprehensible to the ordinary reader, and be relevant to their clinical practice.

Author response: We have done our best to address the comments and do resubmit the manuscript with the according improvements.
To the Editor

Zürich, 15. April 2011

Manuscript: “Contact pressure on ACL hamstring grafts in the bone tunnel with interference screw fixation - dynamic adaptation under load”

authored by: Dominik C Meyer, MD; Michael Stalder, MD; Peter P Koch, MD; Jess G. Snedeker, PhD; Mazda Farshad, MD

Dear Editor,

This is to confirm that none of the authors has an conflict of interest in anyway that could have influenced the above mentioned manuscript.

Yours sincerely,

The authors
Abstract

**Introduction:** Interference screws used in fixation of anterior cruciate ligament (ACL) hamstring grafts create mechanical hold by forcing the graft into frictional contact with the bone tunnel. We analyzed the resultant graft-tunnel contact pressure using an in vitro model of human cadaver 8mm hamstring grafts.

**Methods:** Contact characteristics were assessed using both pressure sensitive films and a force sensor. Two screw sizes were investigated (8 and 9 mm in an 8mm sawbone tunnel), both with and without a bone wedge between graft and screw. Separately, time dependent relaxation of contact force was recorded over a one hour epoch and associated tendon water loss was measured. Pullout testing of 8mm tendon grafts from 8mm holes in Sawbone and porcine femora were performed after 1 minute and 1 hour.

**Results:** During screw insertion, measured peak pressures (>40 MPa) exceeded the compressive failure stress of metaphyseal bone by more than an order of magnitude. Using a bone wedge between tendon and screw reduced local peak pressure by 85% but produced also inferior average contact pressure. In all approaches, initially achieved graft contact pressure rapidly decreased to approximately 25% within 30 minutes. Pullout strength was significantly reduced after 1 hour in comparison to 1 minute in porcine bone as well as Sawbone.

**Conclusion:** Viscoelastic adaptation of the tendon is severe and critically reduces effective graft-bone contact pressure. Consideration of this new effect may open new and improved approaches for tendon graft fixation.

**Key words:** Contact pressure; ACL hamstring graft; interference screw
Contact pressure on ACL hamstring grafts in the bone tunnel with interference screw fixation - dynamic adaptation under load

Authors:
Dominik C Meyer, MD; Michael Stalder, MD; Peter P Koch, MD; Jess G. Snedeker, PhD; Mazda Farshad, MD

Affiliation: Balgrist University Hospital, University of Zürich, Zürich, Switzerland

Running title: Contact pressure on ACL hamstring grafts

Corresponding Author: Mazda Farshad, MD
Address: University of Zürich, Balgrist Forchstrasse 340 8008 Zurich Switzerland
Tel: 0041 44 386 57 52
E-mail: mazda.farshad@balgrist.ch
Contact pressure on ACL hamstring grafts in the bone tunnel with interference screw fixation - dynamic adaptation under load
Abstract

Introduction: Interference screws used in fixation of anterior cruciate ligament (ACL) hamstring grafts create mechanical hold by forcing the graft into frictional contact with the bone tunnel. We analyzed the resultant graft-tunnel contact pressure using an in vitro model of human cadaver 8mm hamstring grafts.

Methods: Contact characteristics were assessed using both pressure sensitive films and a force sensor. Two screw sizes were investigated (8 and 9 mm in an 8mm sawbone tunnel), both with and without a bone wedge between graft and screw. Separately, time dependent relaxation of contact force was recorded over a one hour epoch and associated tendon water loss was measured. Pullout testing of 8mm tendon grafts from 8mm holes in Sawbone and porcine femora were performed after 1 minute and 1 hour.

Results: During screw insertion, measured peak pressures (>40 MPa) exceeded the compressive failure stress of metaphyseal bone by more than an order of magnitude. Using a bone wedge between tendon and screw reduced local peak pressure five-fold by 85% but produced also inferior average contact pressure. In all approaches, initially achieved graft contact pressure rapidly decreased to approximately 25% within 30 minutes. A corresponding drop in graft weight of 20-30% was attributed to tendon water loss. Pullout strength was significantly reduced after 1 hour in comparison to 1 minute in porcine bone as well as Sawbone.

Conclusion: Viscoelastic adaptation of the tendon is severe and critically reduces effective graft-bone contact pressure. Consideration of this new effect may open new and improved approaches for tendon graft fixation.

Key words: Contact pressure; ACL hamstring graft; interference screw
Introduction

Interference screws have found widespread clinical application, particularly for graft fixation in anterior cruciate ligament reconstruction. For the case of hamstring autograft fixation, the screw forces the tendon graft into contact with the bone tunnel, creating pressure, friction and subsequent mechanical stability. Techniques in which an interpositional bone wedge is placed between the screw and the tendon have also been introduced, in an effort to decrease the risk of damage to the tendon and to create a more even and circumferential bone contact\textsuperscript{1-3}. However, even though often used, the mechanical performance of both approaches might have the potential for optimization.\textsuperscript{3,4}

Despite the large number of surgical procedures employing interference screws, little is known regarding the graft-bone contact induced by the screw. Such data is critical to understanding the relative efficacy of the various techniques, and for guiding attempts to improve upon them. This study attempted to mechanically characterize tendon graft-bone contact using both direct interference screw and indirect bone wedge fixation techniques. We hypothesized that the expansive force and local contact pressure will be largely influenced by the screw diameter. We further hypothesized that the viscoelastic adaptation of the tendon results in decreased contact over time and that therefore the mechanical performance of the fixation may be affected with time.

Material and Methods

Graft preparation
Twenty-seven fresh human hamstring tendons (semitendinous and gracilis tendons) were harvested with a stripper from cadavers and stored at -20°C. Tendons were allowed to thaw at room temperature before subsequent warming to 37° and were then dissected from surrounding muscle and fat tissue. Both ends were secured with a 2-0 Vicryl suture (Ethicon, Somerville New Jersey, U.S.A.) and the sample was folded three to four times around Ethibond sutures size 0 (Ethicon) to achieve a tendon transplant with an approximate diameter of 8 mm and a length of 3 cm. Tendons were randomly assigned to four groups; either direct interference screw fixation technique with a 8 mm (n=6) or 9 mm (n=5) interference screw, or using an indirect bone wedge fixation technique (Fig. 1) with a 8 mm (n=6) or 9 mm (n=5) interference screw. In a fifth group (n=5), the temporal evolution of average contact pressure was assessed using the direct fixation method and an 8 mm screw.

To assess pullout strength from porcine bone and Sawbone, 8mm bundles with 3 strands with a length of 12cm were prepared as above from calf extensor tendons, which have almost identical dimensions as human semitendinosus tendons.

Sawbone preparation

Testing was initially performed using fresh porcine femoral condyles as a human test surrogate. However, due to poor performance of the pressure indicating film in the humid environment of actual bone, and observed experimental variation attributed to heterogeneity of the porcine bone density and structure\textsuperscript{1,5}, composite polyurethane foam sawbone blocks were used as a test surrogate for human bone (Nr 1522-11, Sawbones Europe AB, Malmö, Sweden). The cancellous region of the bone had a density of 20g/cc \textsuperscript{6} and were laminated with a 1 mm cortical layer of 64g/cc polyurethane foam. Blocks were cut to dimension of 4 x 3 x 5 cm. A blind hole with a diameter of 8 mm and a depth of 2.75 cm was drilled into the center of the sawbones starting from the
laminated (cortical) side. To allow measurement of expansion force created during screw insertion, each sawbone block was cut in half, going through the center of the predrilled hole. For the bone wedge fixation technique, a 4 mm semicircular bone wedge (Fig.1) was produced on the screw side of one half of each sawbone pair, using a standard surgical chisel (Karl Storz, Tuttlingen, Germany).

For pullout testing, the Sawbone blocks were prepared as above, however without longitudinal cut. For pullout testing form porcine bone, fresh distal porcine femora were removed from all soft tissue and a bicortical 8mm hole was drilled at the anatomical origin of the ACL.

**Experimental setup and procedure**

Pressure indicating films (Prescale Fujifilm, Tokyo, Japan) were wrapped with a cover (Opsite, Smith&Nephew, Solothurn; Switzerland) for protection against humidity (tendon water loss) during the experiment. Each side of the tendon (bone and screw side or bone and bone wedge side, for direct or bone wedge interposition technique, respectively) was covered with stacked films in two sensitivities (2.5-10MPa (LW) and 10-50MPa (MS)) and sandwiched between each half of the sawbone block pair (Fig. 2). The block was then positioned between steel plates within a modified bench vice to provide compressive load to the system. A force sensor (Kistler model 9021A, Winterthur, Switzerland) was interposed to monitor the expansive force. The blocks were preloaded to 100N compression before screw insertion. A Nitinol guide wire (Karl Storz, Tuttlingen, Germany) was used to insert the interference screw (Megafix, Karl Storz, Tuttlingen, Germany Company, Material: polylactic acid (PLDLLA)) of either 8 mm or 9 mm diameter. While inserting the screw, the expansion force measured at the load cell was documented at every 5 mm of insertion until a full insertion of the screw to 20 mm depth. After full insertion, the pressure indicating film was given time to reach equilibrium, the bench vice was opened, and the films were
carefully removed for photodocumentation. The films were later graded according to the provided manufacture calibration standards by the same investigator (MF) (Prescale Fujifilm, Tokyo, Japan).

In the experimental group examining the evolution of expansive force over time, no pressure sensitive films were used.

For pullout testing, the Sawbone blocks were held flat on the materials testing machine (Zwick 1456, Zwick GmbH, Ulm, Germany), while the porcine femora were held in a specifically designed bone holder with a variable angle, allowing for straight loading on the graft, which was held using a clamp after wrapping in gauze. Insertion of the 8mm Megafix interference screw was performed directly on the testing machine, to be able to immediately pull on the graft after screw insertion. Loading was performed displacement controlled at 20mm/min after 5 cycles of preconditioning the graft between (10 and 50 N).

Statistical analysis

Statistical analysis was made using the software PRISM (Version 4, Graphpad software, La Jolla (CA), USA). Grouped data was tested for normal distribution using the Kolmogorov Smirnov test. ANOVA and students t-test were used for normal distributed data to compare intergroup differences. Correlation was assessed with Pearson Correlation test. Whiskers of the Boxplots define minimal and maximal values in the group data. Level of significance was set with a p of <0.05.

Results

Interface pressures
Peak tunnel-graft interface pressures were significantly lower in the indirect bone wedge fixation technique than in the direct fixation technique for all screw sizes (Fig. 3a). In the case of the 8mm screw, these differences were nearly an order magnitude. While less pronounced, direct screw-graft interface pressures were also higher than the bone wedge-graft pressures (in the indirect bone wedge technique) (Fig. 3b). Interestingly, differences as a function of screw size were only observed for the indirect bone wedge technique and similar for the direct fixation technique (Fig. 3).

Expansion forces

Expansive forces were 29-58% lower in the indirect bone wedge fixation technique than in the direct fixation technique for all screw sizes (p<0.001). Expansive force using a 9 mm screw was 117% and 10% higher than achieved with the 8 mm screw for the bone wedge and the direct technique, respectively (p<0.05 and p>0.05, respectively, Fig. 4a).

In relation to screw insertion depth, contact force was more rapidly achieved with direct fixation (Fig. 4b) and was highly correlated for all groups (r>0.99).

Substantial time dependent force relaxation was observed mainly in the first minutes after screw insertion (Fig. 5).

Comparison of expansion force and mean pressure

We assumed that contact occurred over the projected area of the screw or wedge (width times insertion depth). The resulting mean contact pressure (derived by calculations based on the expansion force for an 8 mm screw that is fully inserted (to a 20mm depth) was 463N/160 mm2
(2.89 MPA) vs 141N/160 mm² (0.88 MPA). The 9 mm screw provided 510/180 mm² (2.83 MPA) and 296/180 mm² (1.64 MPa) of interface pressure, for the direct and indirect bone wedge fixations respectively.

Pullout testing

The results of the pullout tests are given in Figure 6. For testing in Sawbone and porcine bone, there was a significant reduction (p<0.05) in pullout strength after waiting one hour after screw insertion (sawbone: 698±71 to 566±35N and porcine bone: 867±79 to 694±93N). The differences between porcine bone and Sawbone was 173±49N and 132±64N for testing immediately after screw insertion and after one hour were 173±49N and 132±64N in the Sawbone and porcine bone, respectively.

Discussion

The fixation of a hamstring tendon graft in a bone canal using interference screws is simple and conceptually straightforward. The method is easy to perform and effectively seals the canal. However, there are several concerns regarding this technique. First and foremost is that mechanical performance has been reported to be inferior to other fixation techniques, such as cortical fixation or metaphyseal cross-pins²,⁷,⁸. It has been documented that use of a small diameter screw may predispose tendon slippage from the canal⁴ and that with larger screws the graft can be damaged by the screw thread¹. Other concerns regard the imposed anatomical interposition of the screw between one side of the bone canal and the transplant, which hinders direct healing there⁹ and creates a non-physiological graft to bone transition.
The mechanical challenge associated with interference screw fixation derives from the smooth and slippery tendon graft surface; even though it was not the primary scope of the present study to quantify this effect, it is reasonable to argue that high contact pressures are required at the bone-graft interface to achieve sufficient friction to avoid slippage. From a biomechanical standpoint, the required contact pressure combined with the inherent material stiffness mismatch at the graft-bone interface presents a problem for this otherwise attractive fixation method: Cancellous bone is relatively stiff and will fail at interface pressures above 2-4 MPa, while the tendon itself is initially incompressible but will might gradually lose water content (and mechanical resistance) over time. Thus, during the initial screw insertion, the confined tendon is very stiff, forcing the surrounding bone to break and effectively increasing the tunnel size. While the initial mechanical purchase at the graft-bone interface may be adequate (before the tendon has lost water), we have demonstrated here that within 30 minutes the system loses up to 80% of the initial contact pressure expansion force due to a viscoelastic behavior.

In this investigation we also examined the so-called indirect bone wedge fixation technique, which uses a cortical fixation combined with a bone wedge pressed to the canal with an interference screw. This method is intended to avoid damage of the graft by the screw threads, and to allow bone-graft contact on all sides for eventual healing. We demonstrate that using a bone wedge with an interference screw of the same (or even larger) diameter as the tunnel results in substantially reduced focal pressure on the tendon, which might be beneficial for graft nutrition, and result in better healing with regard to complete circumferential contact of the tendon to bone. However, the results we present here support previous reports that an indirect bone wedge fixation provides inferior mechanical hold and may only be useful in sealing of the canal against inflowing joint fluid. There are some inherent limitations to this interpretation of the results, first there was a
longitudinal cut through the hole, which certainly decreases stiffness of the system, leading to an
underestimation of the pressure within the bone canal. Second, we mainly used Sawbone blocks to
avoid excessive moisture on the Fuji films and to increase homogeneity of the test system.
However, the direct comparison in pullout testing suggests that Sawbone may indeed serve as a
valid substitute for bone in this test setup. Third, while the absolute values from the readout of the
pressure sensitive films must be interpreted with caution, as they may have been influenced by the
shear force between screw and bone, the relative distribution of pressure however is most likely
correctly represented.

The key discovery in this work is that substantial and progressive tendon adaptation by water loss
can drastically reduce graft-bone contact pressure by a viscoelastic behavior. That dynamic gradual
adaptation of pressure does have a mechanical impact on fixation strength could be demonstrated
in Sawbone and porcine bone. While the loss in expansion force is more pronounced (Figure 5), it
seems that the loss is not linearly related to the fixation strength (Figure 6). This finding could
motivate towards new preparation methods of the graft before implantation with the aim of
reduction or compensation of the viscoelastic behavior and therefore decrease in loss of contact
pressure after implantation. In summary, considering the time-dependent mechanical performance
of interference screw fixation of tendons might offer room for further technical improvements in
this otherwise attractive fixation method.
References


Legend to the Figures

**Figure 1.** The schematic concept of direct fixation (left) and fixation with interposition of a bone wedge (right) of the tendon graft (T) into the bone (B) with an interference screw (S). (The pressure sensitive films which was located both at the bone side (bs) and at the screw side (ss) of the graft.)

**Figure 2.** From left to right: One sawbone part contains the interference screw and the screw site prescale film. The bone site prescale films are still connected to the other sawbone part. The tendon is removed and shows an adaptive shape to the inserted screw.

**Figure 3.** Bone side (left, 3a) and screw side (right 3b) (see Figure 1) peak pressure of for direct fixation technique and bone wedge interposition with 8 and 9mm interference screws, respectively.

**Figure 4.** Maximal expansive forces for direct fixation technique and bone wedge interposition with 8 and 9mm interference screws, respectively (4a). Expansive force development as a function of insertion depth (1/4 to 4/4) of the interference screw for direct fixation technique and bone wedge interposition with 8 and 9mm interference screws, respectively (4b).

**Figure 5.** Decrease of expansive force over time for direct fixation technique with a 8mm interference screw.

**Figure 6.** Fixation strength of 8mm tendon grafts from Sawbone (right) or porcine bone (left), in straight pulling immediately after (< 1min) or 1 hour after screw insertion.
Figure 3

Bone side peak pressure

Screw side peak pressure

* *p < 0.05
Force development over time

Force (N)

0  50  100  150  200  250  300  350  400  450  500  550  600

0  0.5  1  1.5  2  2.5  3  3.5  4  4.5  5  30-60

time (min)

Figure 5