Punching of femoral tunnel in press-fit ACL reconstruction

Abstract

Purpose Conventional press-fit technique for anterior cruciate ligament reconstruction (ACLR) is performed with extraction drilling of the femoral bone tunnel and manual shaping of the patellar bone plug. However, the disadvantages of this technique include variation in bone plug size and thus the strength of the press-fit fixation, bone loss with debris distribution within the knee joint, potential heat necrosis, and metal wear debris due to abrasion of the guide wire. To overcome these disadvantages, a novel technique involving punching of the femoral bone tunnel and standardized compression of the bone plug was introduced. In this study, the fixation strength was tested and compared to that of the gold-standard interference screw fixation technique in three flexion angle configurations (0°/ 45°/ 90°) in a porcine model. We hypothesized that the newly developed standardized press fit fixation would not be inferior to the gold standard method.

Methods Sixty skeletally mature porcine knees (30 pairs) were used. Full-thickness central third patellar tendon strips were harvested, including a patellar bone cylinder of 9.5 mm in diameter. The specimens were randomly assigned to 10 pairs per loading angle (0°, 45°, 90°). One side of each pair was prepared with the press-fit technique, and the contra-lateral side was prepared with interference screw fixation. Equivalent numbers of left and right-sided samples were used for both fixation systems. A three-way multifactor ANOVA was carried out to check for the influence of a) fixation type, b) flexion angle, and c) side of the bone pair.

Results The primary fixation strength of femoral press-fit graft fixation with punched tunnels and standardized bone plug compression did not differ significantly from that of interference screw fixation (p=0.5128), which had mean loads to failure of 422.4±134.6 N and 445.4±135.8 N, respectively. The flexion angle had a significant influence on the maximal load to failure (p=0.0097). Load values were highest in 45° flexion for both fixations. The anatomical side R/L was not a statistically significant factor (p=0.7888).

Conclusion The primary fixation strength of femoral press-fit graft fixation with punched femoral tunnels and standardized bone plug compression is equivalent to that of interference screw fixation in a porcine model. Therefore, the procedure represents an effective method for ACL reconstruction with patellar or quadriceps tendon autografts including a patellar bone plug.

Keywords ACL reconstruction, press-fit, primary fixation, pullout, biomechanics.
Abbreviations

ACL(R)  Anterior cruciate ligament (reconstruction)
IS      Interference screw
PF      Press-fit
Introduction

Interference screw fixation has been one of the most commonly used fixation techniques in anterior cruciate ligament reconstruction (ACLR) (Wenning 2020, Yan 2021). However, despite the superior fixation strength, there are several disadvantages of metal interference screws, such as permanent hardware retention, diminished pullout strength when the screws are not in line with the femoral bone plug, inadvertent graft advancement or laceration of the graft or passing suture, and most importantly, potential compromise of subsequent surgery and disturbance of postoperative magnetic resonance imaging (Barber 2020). Bioabsorbable interference screws can provide secure initial fixation that is comparable with that of metal interference screws while allowing degradation and subsequent replacement with host tissue without distortion of magnetic resonance imaging (MRI) (Shumobrski 2019, Sundaraj 2020).

However, potential problems associated with bioabsorbable screws are compromised biocompatibility, including foreign body reaction, and synovial reaction (Kramer 2020, Chiang 2019). Therefore, press-fit graft fixation has been introduced.

The press-fit graft fixation technique shows sufficient fixation strength and good clinical results (Akoto 2019, Barié 2020, Horstmann 2021). The advantages of this technique include lesser bone loss, no direct or degradation product related damage of the graft by the implant, no secondary hardware removal, and no interference with MRI. Conventional press-fit techniques involve extraction drilling of the femoral bone tunnel, which is sometimes followed by dilation (Akoto 2019, Shanmugaraj 2021, Brandl 2020, Dargel 2007). The patellar bone plug is shaped manually, which makes reproducible sizing demanding. Extraction drilling leads to bone loss with debris distribution within the knee joint, and it may additionally cause heat necrosis and metal wear debris due to abrasion of the guide wire.

Bone debris generation could be a potential problem as it may persist in the joint for up to 6 months after surgery. Furthermore, it may be responsible for increased post-operative knee effusion (MacDonald 2019) or cyclops lesions (Nagira 2021). Ugutmen et al. suggested that early tunnel enlargement could result from bone necrosis and compacted bony debris created during and after drilling [29]. Furthermore, bone debris may be responsible for generating osteophytes, which result in an erroneously high diagnosis of osteoarthritis on subsequent follow-up radiographs [15]. Cyclops lesion is another complication that may be attributed to residual bone debris (Nagira 2021). Nagira showed that debridement of bony debris in and around bone tunnels significantly reduced the incidence of postoperative cyclops lesions (Nagira 2021). Wnorowsky retrospectively

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reviewed 99 ACLR cases, and 4% of the patients showed metal debris in postoperative radiographs, which was most commonly seen within the intercondylar notch [32]. Despite its high prevalence, the significance and fate of metal and bony debris is neither well documented nor understood.

We introduce a new technique to overcome the potential adverse effects of extraction drilling and manual shaping of the patellar bone plug. The technique comprises stamping of the femoral bone tunnel, followed by standardized compression of the patellar bone cylinder with a custom-made instrument. This technique is easy to perform, minimizes bone and metal debris, and is fully bone preserving. The bone cylinder that is stamped out of the femur can be used to fill up the harvesting defect at the patella.

The objective of this study is to biomechanically evaluate this novel technique with respect to the initial fixation strength in comparison to conventional interference screw fixation. We hypothesize that press-fit fixation with a punched femoral tunnel is not inferior to the gold standard of interference screw fixation. We tested this hypothesis by comparing the ultimate strength of the ACLR in three flexion angle configurations (0°/45°/90°).

Material and methods

Specimens and preparation

Sixty skeletally mature porcine knees (30 pairs) were used. The specimens were stored at -6°C, thawed at room temperature 24 h prior to testing, and kept moist with physiologic saline solution throughout the preparation and testing procedures. Ten pairs were randomly assigned per loading angle (0°, 45°, 90°). In this case, all angles refer to nominal knee flexion angles. Hence, 0° refers to full knee extension with the ACL aligned along the Blumensaat line of the intercondylar notch.

One side of each pair was prepared with the press-fit system, while the contralateral side was prepared with interference screw fixation. Equivalent numbers of left and right-sided samples were used for both fixation systems. The biomechanical testing protocol consisted of a single-cycle load-to-failure test.

Harvesting of bone-patellar tendon grafts

In both groups, a 9-mm-wide central full-thickness patellar tendon strip was harvested, including the attachment site of the tibial tuberosity. The strip was harvested using a custom-made parallel scalpel and an oscillating saw (TRS, DePuy Synthes, USA) (Figure 1). A targeting device was pinned to the patella, and a hollow burr with a 9.4-
mm interior diameter was slipped over the tendon strip from the distal direction to harvest the patellar bone cylinder (Figure 2). The patellar bone cylinder was then shortened to 20 mm with a chisel and outfitted with a #5 fiber wire suture in a baseball stitch technique. The femur was released from soft tissues, and the medial condyle was resected.

**Press-fit fixation**

The patellar bone cylinder was placed into a custom-made compactor (Figure 3). The suture was clamped to the compactor, and the patellar bone cylinder was compressed to a conical shape with an outer diameter of 9.5mm. A 2.5-mm guide wire was introduced to the femoral ACL footprint and oriented towards the 10 o’clock position using a standard targeting device with a 7-mm offset. A 25-mm-deep tunnel of 8.6 mm in diameter was then made using a cannulated punch with a centralizer (Figure 4). Next, the compressed 9.5mm patellar bone plug was pulled into the femoral 8.6mm tunnel using shuttle sutures and gently tapped in until it lay flush with the intercondylar notch (Figure 5). Press-fit fixation is caused by the oversize of 0.9mm of bone plug with respect to femoral tunnel.
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Interference screw fixation

The femoral tunnel was drilled using a 9.0-mm cannulated drill bit. The patellar bone cylinder was pulled into the femoral tunnel using shuttle sutures, and a 9x25-mm bioabsorbable interference screw (Megafix, Karl Storz, Germany) was introduced over a Nitinol guide wire until the screw lay flush with the intercondylar notch.

Mechanical test setup

Mechanical loading of the samples was carried out using a Zwick Z1474 screw-driven test machine with a 10-kN load cell. The tibia was positioned and mechanically fixed inside an apparatus mounted on a bottom plate as shown in figures 7 and 8. The samples were aligned with a loading angle of -45°, 0°, or 45° between the femoral longitudinal axis and loading axis. These angles simulated ACLR loading in 0°, 45°, and 90° knee flexion, respectively. In 0° knee flexion, the ACLR was approximately aligned along the Blumensaat line, whereas in 90° knee flexion, the ACLR was perpendicular to the Blumensaat line (figure 6).

The free end of the tendon was pneumatically clamped on the upper side of the setup. A 10-kN load cell was mounted between the clamping apparatus and the crosshead of the machine. Loading was applied in a displacement-driven mode at 5 mm/s with a preload of 10 N. Each sample was loaded until failure. Failure was categorized as follows: a) tendon tear and b) pull-out of the bone plug. The maximum load ($F_{\text{MAX}}$) of the test construct was determined for every test.

Statistical analysis

$F_{\text{MAX}}$ values of each tested group were statistically checked for a normal distribution using the software Origin 2018 (Saphiro-Wilk test at $p=0.05$). A three-way multifactor ANOVA analysis was carried out with the MATLAB function “anovan” to check for a significant influence of the tested factors: a) fixation type, b) flexion angle, and c) anatomical side (left/right).

Results

Load to failure

The mean load to failure was 422.4±134.6 N for PF fixation and 445.4±135.8 N for IS fixation (Table 1). The 3-way ANOVA showed no significant influence of the "fixation type" ($p=0.5128$) or the "anatomical side" (left/ right, $p=0.7888$) on fixation strength. However, the maximum load to failure was significantly influenced by the factor
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“flexion angle” (p=0.0097) with highest loads in 45° flexion for both groups (PF 488.6±157.8 N and IS 503.4±141.2 N) (figure 7).

**Apparent stiffness**

The three-way ANOVA showed a highly significant influence (p < 0.0001) of the factor “flexion angle” on the apparent stiffness with highest values in 90° flexion for both groups (PF 48.3 ± 21.2 N/mm and IS 41.3 ± 9.5 N/mm) and lowest values in 0° flexion (PF 19.0 ± 3.6 N/mm and IS 15.1 ± 4.2 N/mm) (Fig. 8). Factor “fixation type” was marginally significant (p = 0.05; PF 38.7 ± 19.1 N/mm and IS 32.2 ± 16.3 N/mm), while no significant influence was detected for the factor “anatomical side” (left/ right, p > 0.95).

**Mode of failure**

The predominant failure mode over all flexion angles was tendon tear (84%) for interference screw fixation, whereas press-fit fixation failed equally often due to tendon tear and pull-out (50%) (table 2).

**Discussion**

When testing graft fixation techniques in an animal model, the correct selection of species is important. There seems to be no substantial difference between porcine and human bone with respect to the ultimate strength of interference screw fixation [24]. However, the fixation strength can be biased by inhomogeneity of the bone density between donors, which is especially true if human bone from relatively old donors is used [23]. In this study porcine knee specimens were explicitly chosen because they can be frozen immediately after harvesting, and the age of the donors and bone quality are more uniform than in human specimens [23]. By choosing a randomized paired study design, bone mineral density analysis can be safely omitted because there are hardly any left-right differences in bone quality, especially in young donors [13].

With axial loading of press-fit fixation in a porcine model, Lee et al. [19] reported a mean load of 571 ± 109 N, and Rupp et al. [22] reported a mean fixation strength of 463 ± 215 N. Schmidt-Wiethoff et al. investigated the influence of the loading angle on the primary graft stability [23]. They found that fixation strength increased with rising loading angles. The ultimate failure load of 25-mm bone plugs was 262 ± 40 N at 0°, but it reached
429 ± 49 N at 60° [23]. While axial loading caused bone-plug pull-out, the predominant mode of failure at 60° loading was tendon rupture.

With a 0.4-mm oversize of bone plug with respect to the femoral tunnel, Dargel et al. and Schmidt-Wiethoff et al. achieved fixation strengths of 310-402 N and 262-429 N, respectively [7, 23]. Seil et al. reported higher values of 401-708 N using 1.0-mm oversize [24]. The press-fit fixation strength of 422.4 ± 134.6 N that we found in our study is within the range of the aforementioned studies. We chose a 20-mm bone plug length and an 0.8-mm press-fit. Larger bone plugs increase donor site morbidity and the risk of patellar fracture [26]. A higher oversize of the bone plug with respect to the femoral tunnel might further increase primary fixation strength, but there is higher risk of bone plug fracture and laceration of the quadriceps tendon graft during implantation.

Primary graft fixation should be high enough to withstand tensile forces during rehabilitation. However, no experimental data are available for the forces produced in knee ligaments in vivo. Escamilla et al. found a peak ACL force of 59 N for single-leg squat at 0-90° and 158 N for dynamic seated knee extension, which were both measured using 12 repetitions of maximum dumbbell resistance [10]. Toutoungi et al. found values reaching 396 N for maximum isometric seated knee extension, and Shin et al. reported maximum forces of 1294 N during single-leg landing from running to a stop [25, 28]. While the latter loads by far exceed the fixation strengths of 422.4 ± 134.6 N in this study, it has to be mentioned that exercises that produce such high loads should be performed only at a late stage of ACL rehabilitation, when graft incorporation has already been established. Therefore, the primary fixation strengths in this study are most likely sufficiently high to withstand a conventional rehabilitation program.

Apparent stiffness was significantly influenced by knee flexion angle with lowest values in 0°. This might be caused by alignment of the patellar tendon graft along the Blumensaat line when tension was applied resulting in lower stiffness values than in 45° and 90°, where the graft was in no contact to surrounding bone. The differences in failure modes observed with the two fixation techniques may provide some insight into the marginally higher stiffness of PF fixation compared to IS fixation. Whereas IS fixation predominantly failed due to tendon tear (84%), PF fixation failed equally often due to tendon tear and pull-out (50%). While the latter causes an instant drop in fixation force recorded by the testing machine, tendon tear is a slower and more sequential process where some tendon fibers fail first before others follow, resulting in lower stiffness values.
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190 It is not surprising that tendon tear was more frequent with IS fixation as interference screws squeeze the graft against the bone tunnel and, therefore, bear the risk of graft weakening due to laceration [11, 20].

191 In this study, an anatomical loading scenario when the knee is in a flexion position at 0 to 90°, was chosen. Axial loading of the femoral fixation (i.e., loading along the axis of the femoral tunnel) represents an artificial laboratory situation that rarely ever occurs in real life. As the femoral tunnel is drilled over the anteromedial portal in maximal knee flexion, the tunnel is oriented approximately 60° (i.e., the 10 o’clock position) in the frontal plane [14] and approximately 45° in the sagittal plane [5, 6] with respect to the longitudinal axis of the femur. However, when the knee is in extension, the ACL aligns along the Blumensaat line and is oriented nearly perpendicular to the femoral tunnel in the sagittal plane and around 60° in the frontal plane (figure 9). As the knee is flexed towards 90°, the angle in the sagittal plane decreases to 0°, but the frontal plane angle remains around 60°. Hence, axial loading of the femoral fixation is a non-realistic scenario.

200 A few limitations apply to this study. Due to the fact that a porcine knee model was chosen and the mechanical properties of both the femoral and patellar bone have not been particularly investigated, the transferability of the present results to a human ACL reconstruction in vivo might be limited. Furthermore, the initial press-fit fixation strength was investigated and no statement about graft behavior subjected to cyclic loading can be made. This study however shows promising results of the proposed technique. Therefore, the novel technique might represent an alternative reproducible method for ACL reconstruction with patellar or quadriceps tendon autografts including a patellar bone plug. However, clinical studies are needed to evaluate whether it is a safe and effective technique in daily practice.

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Conclusion

211 The primary fixation strength of femoral press-fit fixation with punched femoral tunnels and standardized compression of the patellar bone plug is equivalent to that of interference screw fixation in a porcine model. This procedure minimizes bone and metal debris and represents a standardized technique that is easy to use.

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215 none.
Authors' contributions

JH designed the study, composed the manuscript concept, and wrote the manuscript. SV, AA, and TO conducted the biomechanical tests, performed all statistical analyses, and edited the complete manuscript. MH and JH operated on all cases and helped in editing the final draft version of the manuscript. SE supervised the study and helped in editing the final draft version of the manuscript. All authors read and approved the final manuscript.
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Figure legends

Figure 1: Harvesting of central full-thickness patellar tendon including insertion at tibial tuberosity
Figure 2: Harvesting of patellar bone cylinder
Figure 3: Bone compactor transforms patellar bone cylinder to conical shape
Figure 4: Punching of femoral bone tunnel
Figure 5: Tapping in patellar bone plug into femoral tunnel
Figure 6: Test setup simulating ACL loading in 45° (left) and 90° (right) knee flexion
Figure 7: Ultimate failure loads (Fmax) of press-fit (PF) and interference screw (IS) fixation in 0°/45°/90° knee flexion.
Figure 8: Apparent stiffness of press-fit (PF) and interference screw (IS) fixation in 0°/45°/90° knee flexion.
Figure 9: Illustration of the relationship between the femoral tunnel and the ACL graft in the frontal plane (A) and sagittal plane (B) of a right knee.

Table legends

Table 1: Mean ± standard deviation values of load to failure (Fmax).
Table 2: Failure modes.

Compliance with ethical standards

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