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Soft-tissue graft fixation in posterior cruciate ligament reconstruction: evaluation of the effect of tibial insertion site on joint kinematics and in situ forces using a robotic/UFS testing system

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Abstract *Introduction:* Surgical reconstruction of the posterior cruciate ligament (PCL) is recommended in acute injuries that result in severe tibial subluxation and instability. The surgical outcome level may be affected by the tibial fixation site. In response to a 110-N posterior tibial load, kinematics and in situ forces of anatomical soft-tissue graft fixation in single-bundle PCL reconstruction using an interference screw fixation are significantly closer to those in the intact knee than with extracortical fixation with two staples. *Materials and methods:* Using a robotic/universal force moment sensor (UFS) testing system, we examined joint kinematics and in situ forces of porcine knees following single-bundle PCL reconstruction fixed at two different tibial fixation sites: anatomical interference screw and extracortical fixation. *Results:* The site of the tibial graft fixation had significant effect on the resulting posterior displacement and in situ forces of the graft. Both PCL reconstruction techniques reduced the posterior tibial translation significantly. Proximal fixation techniques provided significantly less posterior tibial translation than extracortical fixation. Single-bundle PCL reconstruction with an interference screw showed higher in situ forces of the graft than the extracortical fixation. *Conclusions:* The kinematics and in situ forces of a single-bundle PCL reconstruction using an interference screw fixation

technique are superior to the primary stability of an extracortical fixation with staples.

Keywords Knee · Posterior cruciate ligament · Hamstring graft fixation · Anatomical fixation site · Kinematics · Robotics

Introduction

Statements from the literature regarding the treatment of posterior cruciate ligament (PCL) injuries are controversial. Despite promising short-term results after conservative treatment several studies on the natural history of PCL insufficiency suggest that late knee arthrosis develops in 8–36% of patients with untreated PCL insufficiency [4, 10, 40]. PCL reconstruction has been recommended in severe PCL injuries and in injuries combined with other injuries [1, 8, 11, 12, 19, 31, 32, 36]. Current techniques for reconstruction of the PCL have yielded inconsistent results and do not appear to eliminate abnormal posterior laxity [2, 9, 13, 26, 29, 33, 34, 38]. In addition to variables such as graft choice, position of the knee at the time of fixation, number of bundles reconstructed, tunnel and inlay technique, and tunnel position, the fixation site at the tibia may play an important role in determination of surgical outcome [16, 17, 21, 39, 35, 42, 45]. Many fixation techniques of a soft-tissue graft are available [19, 20, 25]. Most of these were originally developed for anterior cruciate ligament (ACL) reconstruction and have been adapted for use in PCL reconstruction [25]. Biomechanical studies have shown that in ACL reconstruction extracortical graft fixation with soft-tissue washer is the technique that provides the highest fixation strength [5, 25, 37]. However, these fixation techniques provide only a low stiffness compared to an intact ligament or bone–patellar tendon–bone graft [3, 25, 27]. In both ACL and PCL reconstruction this can theoretically lead to micromotion of the graft within the tunnel which might distort tendon to bone healing [24, 27]. For ACL reconstruction some authors recommend anatomical fixation of soft-tis-

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sue grafts close to the joint line to overcome these disadvantages. To achieve this the most common technique is the interference screw technique as introduced by Lambert et al. in 1983 [28]. Since there are obvious differences in the direction of the tibial tunnel and the intra-articular course of the graft between ACL and PCL reconstruction, the basic science studies about ACL graft fixation cannot be applied to PCL reconstruction. Thus the research question of the present study is whether these both tibial fixation sites (extracortical and anatomical graft fixation) are as effective in establishing resistance to posterior tibial translation and restoration of the in situ forces of the intact PCL.

The present study evaluated the effect of two different fixation sites on the tibia for the replacement of the PCL, i.e., an extracortical fixation using bone staples and an anatomical fixation with interference screws, in response to a 110-N anterior-posterior tibial load. These two fixation levels were chosen because of their widespread clinical use. We hypothesized that in response to a 110-N posterior tibial load the kinematics and in situ forces of anatomical soft-tissue graft fixation in single-bundle PCL reconstruction using an interference screw fixation would be significantly closer to those of the intact knee than with extracortical fixation with two staples. To test this hypothesis a robotic/universal force-moment sensor (UFS) was established to investigate the knee kinematics in multiple degrees of freedom and to determine the in situ forces in intact PCL and soft-tissue graft following these two reconstruction techniques.

Material and methods

Specimen preparation

Ten fresh frozen skeletally mature porcine knees were used as described by Ishibashi et al. [27] and Tsuda et al. [47]. This model was selected because of the similarity between the human and the porcine knee [15]. The material was obtained from a local abattoir, fresh frozen at -20° and thawed 12 h prior to testing at room temperature. All muscles except the popliteus muscle were removed, leaving the capsule and the ligaments intact [27]. Femur and tibia were cut approx. 15 cm from the joint line and secured in thick-walled aluminum cylinders using polymethylmethacrylate bone cement (Palacos, Merck, Darmstadt, Germany). The femoral cylinder was mounted to the base of the robot (KR 125, KUKA Robots, Augsburg, Germany) with a custom-made clamp while the tibial cylinder was connected through a universal force moment sensor (UFS; FTI Theta 1500-240, Schunk, Lauffen, Germany). The UFS was firmly fixed to the end-effector of a robotic manipulator with six degrees of freedom (Fig. 1).

Since porcine hamstring tendons are too short to be used for the PCL reconstruction, in this study the tendon grafts were harvested from the porcine flexor digitorum tendons. The grafts of a defined length of 15 cm were immediately stored at -20°C after harvesting. Prior to testing all tendons were thawed at room temperature for 12 h and kept moist with saline irrigation during preparation to prevent exsiccation. All tendons were folded to two stranded tendon grafts. A whip stitch was used to sew the strands to each other in a standard fashion, and the diameter of the graft was determined using sizing tubes.

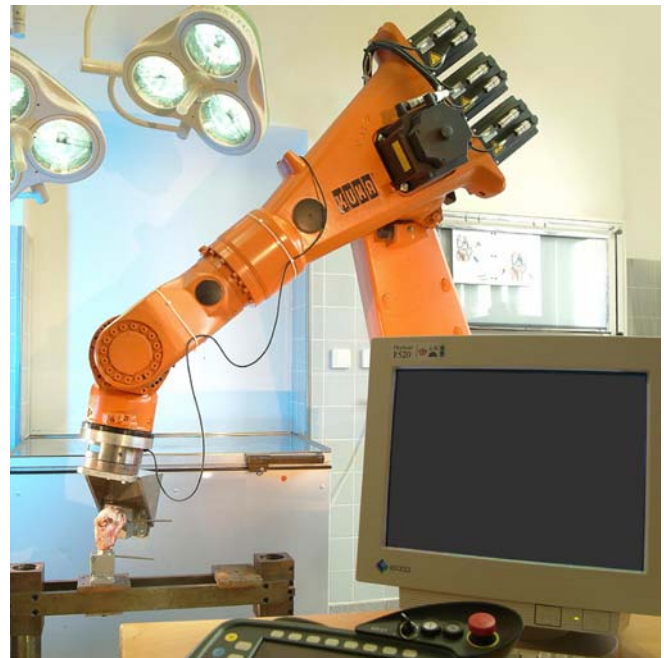


Fig. 1 A porcine knee mounted on the robotic/UFS testing system

Robotic/UFS testing system

A testing system was used to measure knee kinematics that combines robotic technology with a UFS as described by Woo et al. [6, 7, 14, 18, 20, 21, 22, 23, 27, 30, 44, 47, 49, 50]. This technique has been used in a number of biomechanical research studies to evaluate the effect of surgical techniques on knee kinematics and in situ forces of the knee ligaments and is well established [6, 7, 14, 18, 20, 21, 22, 23, 27, 30, 44, 47, 49, 50]. The robot is a six-joint, serially articulated manipulator which allows knee movement in six degrees of freedom. The repeatability of this system is 0.2 mm and 0.02° for orientation and position of the end effector. The robotic manipulator is capable of achieving positional control of the knee in six degrees of freedom, while the universal force moment sensor can measure three orthogonal forces and moments. Simultaneously this system operates in a force-controlled mode via the force feedback from the universal force moment sensor to the robot [6, 7, 14, 18, 20, 21, 22, 23, 27, 30, 44, 47, 49, 50].

Testing protocol

The path of passive flexion-extension of the intact knee joint was determined by the robotic/UFS testing system by maintaining a target force and moment of zero in all remaining degrees of freedom (Table 1). Since a porcine knee joint cannot fully extend, the system found the positions of the knee that minimized all external forces and moments applied to the joint throughout the range of flexion from 30° to 90° in increments of 1° . The positions determined through this procedure served as the starting point for application of external loads.

To perform anterior-posterior (AP) translation tests the robot moved the joint to the desired flexion angle and applied an external AP load. Cyclic AP loading of 110 N was applied to the specimen at 30° , 60° , 75° , and 90° of flexion, while allowing knee movement in five degrees of freedom. All positions and orientations of the joint under this external loading were recorded by the robot. AP displacement was used to simulate clinical posterior drawer examination used to diagnose PCL deficiency. The PCL was then transected through a small parapatellar incision to simulate an isolated PCL tear. After PCL transection the capsule was

Table 1 Testing protocol and data obtained

Protocol	Data obtained
Intact knee	
Path of passive flexion-extension	Intact knee kinematics
Load application (110 N anterior-posterior)	
PCL transection	
Repeat recorded kinematics	In situ force of the intact PCL
Load application (110 N anterior-posterior)	PCL-deficient knee kinematics
PCL reconstruction: extracortical fixation	
Load application (110 N anterior-posterior)	Kinematics PCL reconstructed knee (extracortical fixation)
Graft release	
Repeat recorded kinematics	In situ force PCL graft (extracortical fixation)
PCL reconstruction interference screw fixation	
Load application (110 N anterior-posterior)	Kinematics PCL reconstructed knee (interference screw fixation)
Graft release	
Repeat recorded kinematics	In situ force PCL graft (interference screw fixation)

closed using a 3-0 Dacron suture (Braun, Spangenberg, Germany). The previously determined five degrees of freedom in kinematics of the intact knee were then repeated by the robotic manipulator in a position-control mode, while the UFS recorded a new set of force and moment data. Using the principle of superposition, the vector difference in forces measured before and after the PCL was sectioned can be attributed to the PCL because identical knee motions were repeated [6, 7, 14, 18, 20, 21, 22, 23, 27, 30, 44, 47, 49, 50]. This change in force was then called the in situ force in the PCL [7, 14, 20, 23, 30, 44, 49, 50]. To assess the stability of the PCL deficient knee joint the robot then reapplied external loading of 110 N to the specimen at 30°, 60°, 75°, and 90° of flexion, while allowing knee movements in five degrees. The AP displacements were again recorded for comparison to the intact joint.

Surgical technique and reconstructed knee testing

Reconstruction of the PCL was performed using the same small parapatellar incision that was used for PCL transection. On the tibial side the PCL stump was removed prior to drilling, and the medial meniscal root was used as landmark for tibial tunnel position. The entrance to the tunnel was located medial to the tibial tubercle. Using a tibial aimer (PCL Femoral Adapter Guide Marking Hook, Arthrex, Naples, Fla., USA), a 2.4-mm Kirschner (K) wire was centered in the tibial insertion of the PCL, approximately 13 mm below the joint line in a 50° angle to the tibial plateau. The tibial drill guide was removed, leaving the guide wire firmly attached to the bone. While a curette was used to prevent protrusion of the pin into the popliteal area, the anterior cortex of the tibial tunnel was opened by using a cannulated drill bit over the guide wire. To prevent damage to the neurovascular structures a hand-driven trans-tibial tube saw was then used to penetrate the dense posterior subchondral bone and to remove the remnants of the old PCL [46]. Once the tube saw entered the joint, it was advanced further with an oscillating motion to resect all soft-tissue fibers remaining at the tunnel exit [46]. The tibial tunnel was then dilated up to the desired diameter of the tunnel using cannulated tibia dilators. On the femoral side, a K-wire was used to mark the entrance of a single-bundle tunnel, replacing the anterolateral bundle. The K-wire was placed in the center of the anterolateral bundle according to the anatomical description by Petersen and Tillmann [41]. The tunnel was drilled approximately 7–8 mm from the articular cartilage margin and 7–8 mm from the top of the notch roof. Appropriately sized dilators were inserted and driven into the bone at the previously marked entry point and advanced to approx. 30 mm. For femoral fixation a hybrid technique was used. The proximal 25 mm of the graft was pulled into the tunnel in an inside-out fashion. Extracor-

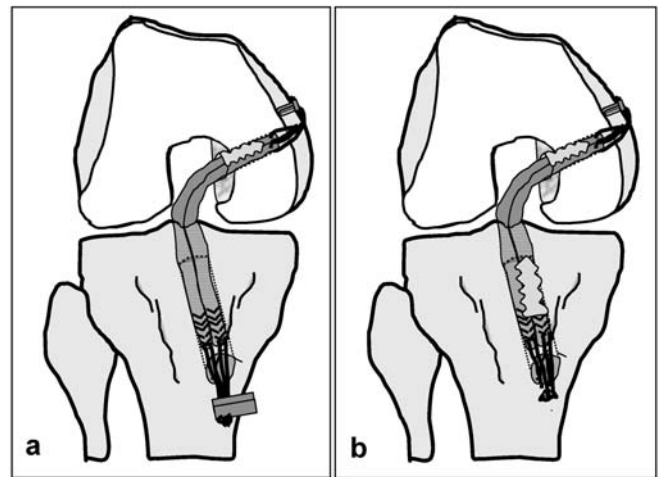


Fig. 2 Schematic drawing of the tibial fixation sites of the PCL replacement graft tested in the study. The femoral side of the graft was fixed with a hybrid technique (extracortical fixation with a staple and 7×23 mm interference screw; Absolute). **a** Extracortical tibial fixation using two bone staples. **b** Anatomical interference screw fixation (Absolute)

tical fixation was then achieved by securing the holding tape (Dexon 0, Braun) with a bone staple. Subsequently a biodegradable 7×23 mm interference screw (AbsoluteAbsorbable Interference Screw, Innovative Devices, Marlborough, Mass., USA) was screwed into the femoral bone tunnel to ensure anatomical femoral fixation. The distal end of the graft was pretensioned to 80 N using a calibrated spring scale and fixed to the tibia as described below. At the tibial site two different fixation locations were studied: (a) extracortical fixation using holding tape and two bone staples and (b) anatomical interference screw fixation (Fig. 2).

Extracortical fixation was performed using bone staples to fix the graft via linkage tape (Dexon 0, Braun) to the tibia. Prior to fixation the grafts were preconditioned by moving the knees between 30° and 90° of knee flexion 15 times. The graft was fixed at 90° of flexion in an anterior drawer. With the application of 80 N pretension, a staple was inserted 5 mm distal to the entrance of the tibial tunnel, and six knots were used to secure the fixation. To obtain the graft forces the graft was detached by reharvesting the tibial staples after testing. In the second group graft fixation was per-

formed using a 7×23 mm biodegradable interference screw (Absolute) in an outside-in technique. Similar to the extracortical fixation the graft was fixed with 80 N pretension in an anterior drawer at 90° of knee flexion. After obtaining the data for the posterior tibial translation, the interference screw was retrieved to obtain the graft forces. Every screw was used once for the fixation of the graft.

To assess the stability of the PCL-reconstructed knee five cycles of AP loading of 110 N were applied to the joint at 30°, 60°, 75°, and 90° of flexion while allowing knee movements in five degrees of freedom. The resulting AP translations of the joint were recorded. To determine the in situ forces in the replacement graft the distal fixation of the graft was released after each reconstruction, and the robot was used to reproduce the motion of five degrees of freedom in the reconstructed joint with the knee at 30°, 60°, 75°, and 90° of flexion and to record the occurring forces and moments.

Statistics

All four knee conditions (intact, PCL-deficient, reconstructed with extracortical, and anatomical fixation) were tested in one specimen. Therefore statistical analysis was performed using a two-factor repeated measures analysis of variance. Knee condition (intact, PCL-deficient, PCL-reconstructed) and flexion angle were the two investigated factors. The dependent variables investigated were knee kinematics and in situ forces in the PCL and PCL graft. The significance level was set at $P < 0.05$.

Results

Knee kinematics

In response to the 110-N posterior tibial load the greatest mean posterior tibial translation of the intact knee was of 4.30 ± 1.0 mm at 30° of knee flexion (Table 2). Posterior tibial translation significantly increased at all flexion angles after transection of the PCL ($P < 0.05$). The greatest mean increase in posterior tibial translation after transection of the PCL was 19.9 mm and occurred at 90° of knee flexion (Table 2). Transection of the PCL did not affect the anterior tibial translation. Both PCL reconstruction techniques resulted in significantly less posterior tibial translation at all flexion angles than in the PCL-deficient knee ($P < 0.05$).

After reconstruction of the PCL using an extracortical fixation technique the mean increase in posterior tibial translation was reduced to 5.2 ± 1.7 , 7.1 ± 1.6 , 8.0 ± 1.6 , and 8.4 ± 1.3 mm of that of the intact knees at 30°, 60°, 75°, and

Table 2 Anterior tibial translation (mm) in response to posterior tibial translation. The values are given as the mean and the standard deviation

Position of knee flexion	Intact	PCL deficient	PCL reconstructed	
			Extracortical fixation	Interference screw fixation
30°	4.3±1.0	12.3±2.3	9.5±2.7	5.7±1.1
60°	3.6±1.3	19.2±2.4	10.7±2.9	5.5±1.4
75°	3.4±0.8	21.3±2.1	11.3±2.5	5.7±1.5
90°	4.1±1.0	24.1±1.8	12.6±2.2	6.2±1.8

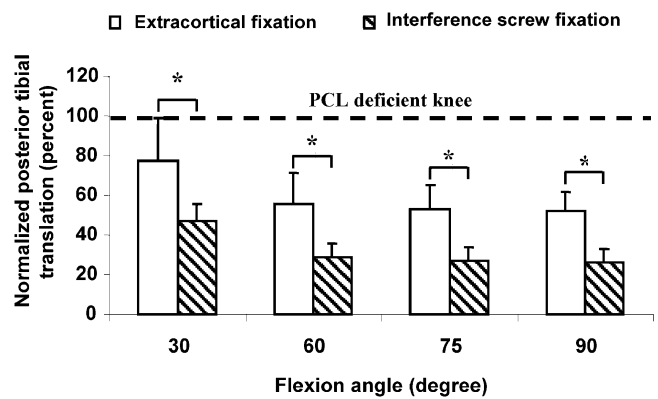


Fig. 3 Posterior tibial translation in the reconstructed knees, normalized to that in the knees with a deficient ligament, in response to a 110-N posterior tibial load. The values are given as the mean and the standard deviation. $*P < 0.05$

90° of flexion, respectively (Table 2). After reconstruction with an interference screw technique close to the joint line the mean increase in posterior tibial translation was reduced to 1.4 ± 1.1 , 1.9 ± 1.4 , 2.4 ± 1.5 , and 2.0 ± 1.2 mm of that of the intact knees at 30°, 60°, 75°, and 90° of flexion, respectively (Table 2). When the data were normalized with respect to those for the knees with a deficient PCL, the mean posterior tibial translation at 90° of knee flexion after reconstruction with extracortical and interference screw technique was reduced to 52% and 26%, respectively, of that in the knees with a deficient ligament (Fig. 3). The differences in posterior tibial translation between extracortical fixation and interference screw fixation was statistically significant ($P < 0.05$).

In situ force in the PCL and the PCL replacement grafts

The magnitude of the in situ forces of the native PCL increased at higher knee flexion angles. In response to a 110-N posterior tibial load the in situ forces were found to increase from 65 ± 16 N at 30° to 94 ± 20 N at 90° of knee flexion (Table 3). The in situ force in the replacement graft was significantly affected by the knee flexion angle ($P < 0.05$). Both reconstruction techniques followed the same trend, i.e., the in situ forces of the graft increased at higher flexion angles up to 71 ± 18 and 81 ± 17 N at 90° of knee flexion for extracortical and interference screw tech-

Table 3 In situ forces (N) in response to 110 N posterior tibial load. The values are given as the mean and the standard deviation

Position of knee flexion	Intact PCL	PCL reconstructed	
		Extracortical fixation	Interference screw fixation
30°	65±16	42±13	51±17
60°	82±18	58±15	68±13
75°	87±17	63±16	76±12
90°	94±20	71±18	81±17

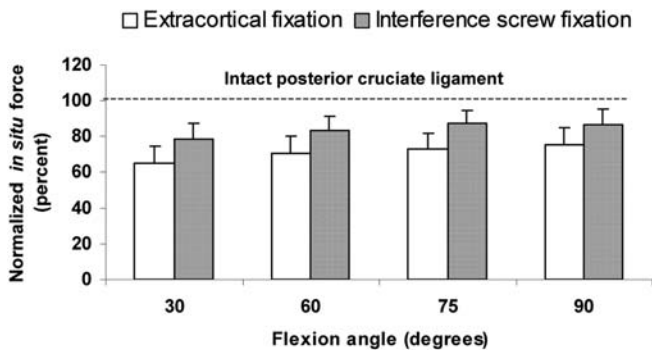


Fig. 4 In situ force in the graft, normalized to that in the intact posterior cruciate ligaments, in response to a 110-N posterior tibial load. The values are given as the mean and the standard deviation

nique, respectively (Table 3). When comparing the in situ forces of the graft it is convenient to normalize the data with respect to those for the intact PCL (Fig. 4). The mean normalized in situ forces in the graft were $76\pm 19\%$ and $86\pm 18\%$ after extracortical and interference screw fixation, respectively, of that in the intact PCL at 90° of flexion (Fig. 4). The differences in the in situ force between in the grafts after reconstruction using both techniques and the intact PCL were statistically significant ($P < 0.05$).

Discussion

This study investigates the effect of two different tibial fixation sites for the replacement of the PCL (extracortical fixation vs. anatomical fixation) on knee kinematics and in situ forces in response to 110 N AP tibial load. The data obtained were then compared to the properties of the intact knee. To accomplish this a robotic testing system with a UFS was established and utilized to examine the two fixation levels. We found that the site of PCL graft fixation at the tibia significantly affects the resulting knee kinematics. With an anatomical graft fixation close to the joint line using interference screws, kinematics of the normal knee and in situ forces of the normal PCL can be restored more closely than with an extracortical fixation with bone staples.

The two reconstruction techniques were tested using the robotic/UFS testing system in the same knee, and the results of these reconstructions were compared to biomechanical findings in the intact knee. This substantially minimizes interspecimen variability. Another advantage of the robotic/UFS testing system is that it reproduces intact knee motion. This allows comparing directly the effects of different PCL reconstruction techniques [20, 21, 22, 49, 50]. All knee kinematics were determined with respect to the path of passive flexion extension of the intact knee, and thus a consistent and repeatable reference position was available from which knee kinematics could be measured. Both PCL reconstruction techniques significantly reduced the posterior tibial translation compared to the PCL-deficient knee ($P < 0.05$). The values found in this study are in accordance with those from other biomechan-

ical studies evaluating joint kinematics of the PCL-injured knee using a robotic/UFS testing system [23, 48]. From a clinical point of view the results after PCL reconstruction have not been as predictable as those for ACL reconstruction [32, 36, 38]. Mariani et al. [32] performed PCL reconstructions in 24 patients with an isolated PCL tear using bone–patellar tendon–bone autografts using an interference screw technique. In response to 89 N posterior tibial force the postoperative laxity measurements at 26.5 months follow-up averaged 4.08 mm side-to-side difference at 70° of knee flexion. Normal laxity (side-to-side difference of 0–2 mm) was restored in 25% of patients and near-normal laxity (side-to-side difference 3–5 mm) in 54%. In response to a 110 N posterior tibial load, the current study found a posterior tibial translation of 8.0 ± 1.6 and 2.4 ± 0.6 mm for extracortical and interference screw soft-tissue graft fixation compared to the intact knee at 75° of flexion, respectively. Noyes and Barber-Westin [38] performed PCL reconstruction with allograft alone in 10 patients (bone–patellar tendon–bone in 6 patients and Achilles tendon in 4) and with a ligament augmentation device in 15 patients (13 of the 15 had supplementation of the device with a bone–patellar tendon–bone allograft). At an average of 45 months postoperatively the side-to-side difference in posterior laxity was less than 2.5 mm in 25%, 3–5.5 mm in 12%, and more than 6 mm in 63% of patients with chronic PCL injury and 3–5.5 mm in 60% and more than 6 mm in 40% in patients with acute injury.

The current study suggests that the level of tibial fixation plays an important role in PCL reconstruction. To our knowledge no study has previously evaluated the effect of the tibial fixation site on knee kinematics and in situ forces in a PCL reconstructed knee. Our results show that an anatomical graft fixation close to the joint line can restore knee kinematics more closely when compared to the intact knee and are in accordance with biomechanical research studies of the graft fixation site for ACL reconstruction. Ishibashi et al. [27] showed that in ACL reconstruction using a bone–patellar tendon–bone graft the site of graft fixation at the tibia significantly affects the resulting knee kinematics significantly. Using a robotic/UFS testing system distal graft fixation was found to produce significantly lower stability than a proximal fixation using an interference screw [27]. Similar findings have been reported by Tsuda et al. [47] for the femoral fixation of hamstring grafts in ACL surgery. These authors observed a significant increase in the knee stability at a variety of flexion angles when the hamstring graft fixation was placed close to the articular cavity. One explanation of the low stability of extracortical fixation techniques is the low stiffness of the graft/fixation construct. These results of this study underline the importance of matching the stiffness of replacement graft with the stiffness of the native ligament [49, 50]. This can be achieved by reducing the total length of the graft choosing a fixation technique that fixes the graft close to the joint line.

The use of the robotic/UFS system enabled us to determine the magnitudes of the in situ forces within the intact PCL and the PCL grafts [44, 49, 50]. The in situ force is

an important determinant of a PCL reconstruction technique [21, 22]. Both reconstruction techniques tested in this study showed a significant difference in the resulting in situ forces compared to the intact PCL ($P < 0.05$). Since the loading conditions were the same in both reconstruction techniques as well as in the intact knee, other structures such as the menisci, cartilage or the posterolateral structures must provide a greater resistance force to posterior tibial displacement in PCL reconstruction. This may explain why secondary injury to these structures can occur despite of PCL reconstruction. However, both fixation techniques used for the fixation of the single-bundle PCL reconstruction showed significantly lower in situ forces than the intact PCL. Recent biomechanical research has shown that a double-bundle PCL reconstruction can restore the in situ forces of the native PCL without statistical significant differences at 0° and 30° of knee flexion [21, 45]. Further research must investigate different tunnel positions in double bundle PCL reconstruction.

A potential limitation of this study was the use of porcine instead of human material. However, porcine knees have been used in several laboratory investigations utilizing bone patellar tendon bone grafts or hamstring grafts [27, 48]. The relative scarcity of human material from young donors makes it difficult to use it in a laboratory setting, at least in the numbers necessary to obtain statistical meaningful results. A benefit of porcine material is the lack of degenerative components and the inconsistent quality of the bone and soft tissues of human knees obtained from old specimens [15]. Another limitation is that only a double-bundle tendon graft was tested while in the clinical setting quadruple hamstring grafts are most commonly used, and that the order of the different techniques used to fix the PCL graft was not randomized. However, fraying and weakening of the graft due to the insertion of the interference screw made it impractical to alternate the order of the fixation techniques at the tibial site. This biomechanical test setup obtains data only for time point zero without having the possibility of taking the effect of muscles into consideration. In vivo the healing potential of the graft as well as the muscle activity might have a great effect to the kinematics of a PCL reconstructed knee.

In conclusion, this study shows that the robotic/UFS testing system is an ideal tool for biomechanical evaluation of the PCL-deficient knee and the resulting properties in response to external loading conditions. This system enabled us to evaluate the effect of different fixation levels at the tibia on the kinematics of the PCL reconstructed knee and in situ forces in the replacement grafts and to compare these results to the intact knee condition of the same knee. The data suggest that a fixation at the anatomical insertion site can restore normal knee kinematics and in situ forces in the replacement graft more closely than an extracortical graft fixation. Thus this laboratory study provides further insight into the biomechanics of the PCL-deficient knee. Further research studies will evaluate the effect of anatomical graft fixation in double-bundle PCL reconstruction.

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