Original Article With Video Illustrations

Anterior Cruciate Ligament Reconstruction Using Patellar Tendon Versus Hamstring Tendon: A Prospective Comparative Study With 9-Year Follow-Up

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Purpose: To analyze the long-term evaluation of clinical, functional, and magnetic resonance imaging (MRI) results after implant-free press-fit anterior cruciate ligament (ACL) reconstruction with bone–patella tendon (BPT) versus quadrupled hamstring tendon (HT) grafts. **Methods:** Sixty-two ACL-insufficient patients were included in a prospective, randomized study (31 BPT and 31 HT). Both surgical procedures were performed without any implants by a press-fit technique by the senior author. The femoral tunnel was drilled through the anteromedial portal for anatomic placement. At 8.8 years after reconstruction, 53 patients (28 BPT and 25 HT) were examined by different clinical and functional tests. Bilateral MRI scans were performed and interpreted by an independent radiologist. **Results:** On follow-up, the score on the International Knee Documentation Committee evaluation form was significantly better in the HT group. The clinical examination including range of motion, KT-1000 test (MEDmetric, San Diego, CA), and pivot-shift test showed no significant differences. On isokinetic testing, the mean quadriceps strength was close to normal (96%) in both groups, but the hamstring strength was lower in the HT group (100.3%/95.1%). Kneeling (1.5/1.1, $P = .002$), knee walking (1.72/1.14, $P = .002$), and single-leg hop test (95.8%/99.1%, $P = .057$) were better in the HT group. The MRI findings about the mean degree of cartilage lesion (International Cartilage Repair Society protocol) of the operated (2.1/2.1) and nonoperated (1.4/1.8) knee showed no significant differences. No significant difference was found in the grade of medial or lateral meniscal lesion or the number of patients having meniscal lesions when the operated and nonoperated knees were compared. Tunnel measurements, Caton-Deschamps Index, and the sagittal ACL angle were similar. **Conclusions:** The implant-free press-fit technique for anterior cruciate ligament reconstruction by use of bone–patellar tendon and hamstring grafts with anatomic graft placement is an innovative technique to preserve the cartilage and meniscal status without significant differences between the operated and nonoperated knees in the long term. Significantly less anterior knee pain was noted in the hamstring group, when testing for kneeling and knee walking. **Level of Evidence:** Level II, prospective comparative study.

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Rupture of the anterior cruciate ligament (ACL) is a common injury, leading to functional instability of the knee. Such instability has been found to be associated with meniscal and chondral injuries as well as with the development of degenerative disease.[1]

The importance of the ACL as a knee stabilizer is reflected in the large number of techniques that have been developed for the surgical reconstruction of the ACL-deficient knee. Despite the frequency of ACL reconstruction, there are still discrepancies regarding the surgeon's preference of ligament graft choice. A majority of primary procedures are performed with either bone–patellar tendon–bone (BPTB) or hamstring (semitendinosus/gracilis) autografts, combined with various fixation techniques. The functional results of both operative techniques are comparable yet mostly prove that discomfort is higher for the BPTB technique when kneeling.[2,3]

The goal of ACL reconstruction is to provide appropriate stability to allow for good function and to protect the knee from developing cartilage damage, meniscus tears, and osteoarthritis.

In this prospective randomized study we compared clinical and functional long-term results of patients after ACL reconstruction using bone–patellar tendon autograft (BPT; using a single bone) or quadrupled hamstring tendon (HT) autograft with a special interest in the status of intra-articular cartilage, meniscus, and graft morphology using bilateral magnetic resonance imaging (MRI) at the latest follow-up. Both grafts underwent femoral fixation without any implants by a special press-fit technique and tibial fixation over a bone bridge.

We hypothesized that anatomic ACL reconstruction with BPT or quadrupled HT graft fixation close to the insertion sites with a femoral tunnel drilled through the anteromedial portal (AMP) results in similar good clinical, functional, and MRI results but less discomfort in the HT group.

METHODS

Subjects

Seventy-one patients with an acute rupture of the ACL were prospectively randomized to either BPT or HT for ACL reconstruction. All were recreational or competitive athletes. Randomization was done by tossing a coin before the first examination. Exclusion criteria were any concomitant ligament or meniscus injury or previous surgery, evidence of chondral lesion higher than grade 2, and any damage to the contralateral knee. Intraoperative findings and other reasons led to the exclusion of 9 further patients until the 1-year follow-up. Thus the definitive patient cohort comprised 62 patients. Of these patients, 31 (19 men and 12 women) underwent ACL reconstruction with BPT graft and 31 (18 men and 13 women) with quadrupled HT graft (semitendinosus and gracilis tendon). The mean time between injury and surgery was 78.7 days in the BPT group and 77.6 days in the HT group. The mean age of the patients was 29.87 years (range, 25 to 55 years) for BPT and 34.23 years (range, 26 to 64 years) for HT. All patients were operated on between October 1998 and September 1999 by the senior author. They were examined 1 day preoperatively and 1 year and 9 years postoperatively. The preinjury activity level was determined for each individual. The study was approved by our ethics committee.

Surgical Technique

An arthroscopic-assisted technique was used for both grafts (Videos 1-3, available at www.arthroscopyjournal.org).[4]

BPT Graft. A surgical approach with two 2-cm horizontal incisions was used to reduce the risk of infrapatellar nerve lesion. A 10- to 11-mm-wide medial-third patellar tendon strip was harvested including a 25-mm-long and 10-mm-wide bone plug from the tibial tubercle. The graft was stripped of the lower patella pole without any bone but with the adjacent periosteum. This allowed use of a smaller but press-fit tibial tunnel to encourage rapid graft incorporation.

The bone plug was shaped into a cylinder, and 3 Ethibond No. 2 Krackow sutures (Ethicon, Somerville, NJ) were placed through the periosteal portion of the graft.

A 10-mm femoral socket tunnel was created through the AMP in a hyperflexed position by use of a 10-mm drill for the notch cortex, replaced by a 10-mm bone harvesting tube for obtaining bone graft material (Fig 1). The tip of a K-wire was drilled by use of a 6-mm offset femoral guide through the medial portal into the center between the anteromedial (AM) and posterolateral (PL) bundles. The tip position was controlled by use of a lateral C-arm (Fig 2).

On the tibia, a 2.5-mm tunnel was drilled with a drill guide set to an angle of 50° into the center of the tibial AM and PL insertions (Fig 3). The surgeon verified the correct position by placing a so-called impingement probe with a radius of 4 mm onto the drill tip and hyperextending the knee under lateral

Figure 1. Select harvesting tube of an external diameter 1 mm less than the diameter of the graft bone plug; impact into the femur to a depth of 30 mm. Twist tube out, and preserve captured plug of cancellous bone.

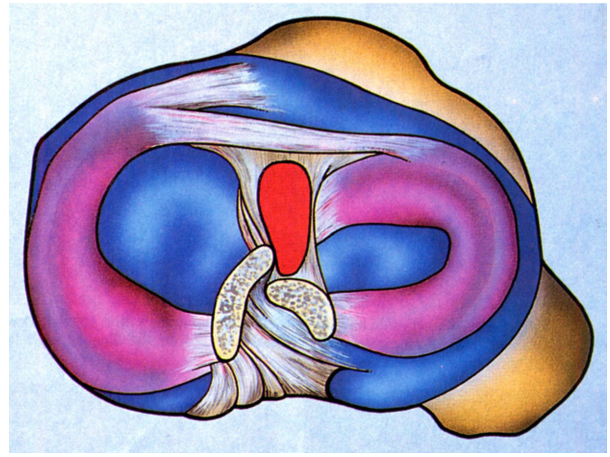

Figure 3. Tibial attachment of ACL.

C-arm control to exclude intercondylar notch impingement before overdrilling with a 6- to 7-mm drill (Fig 4). The bone plug of the graft was then pulled into the femoral tunnel through the AMP with the plug's cortex facing the tibial plateau, thus mimicking an AM and PL bundle position. Then, the bone plug was driven by a press-fit technique into the femoral tunnel with a spiked impactor with the knee flexed to 120° (Fig 5). The distal free end of the graft was then pulled through the tibial tunnel. Tibial fixation was achieved in 10° of knee flexion by creating a 1-cm-wide bone bridge distal to the tibial tunnel outlet and passing 1 arm of the Krackow sutures under this bridge, with tightening under manual tension over the bridge. Additional press-fit fixation was achieved by impaction of the harvested bone plug from the femoral tunnel (Fig 6).

HT Graft. A horizontal 2-cm incision was used to harvest the semitendinosus and gracilis tendons. Both

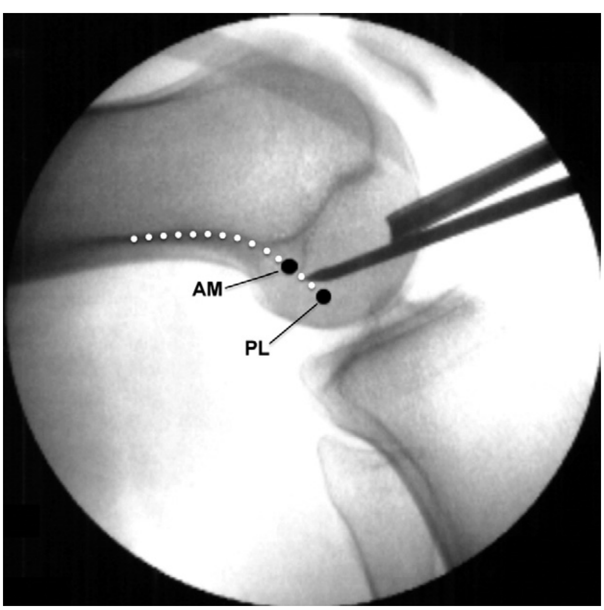

Figure 2. Control of the tip position in the center between the AM and PL bundles by use of a lateral C-arm.

Figure 4. Impingement probe to exclude intercondylar notch impingement with lateral C-arm control.

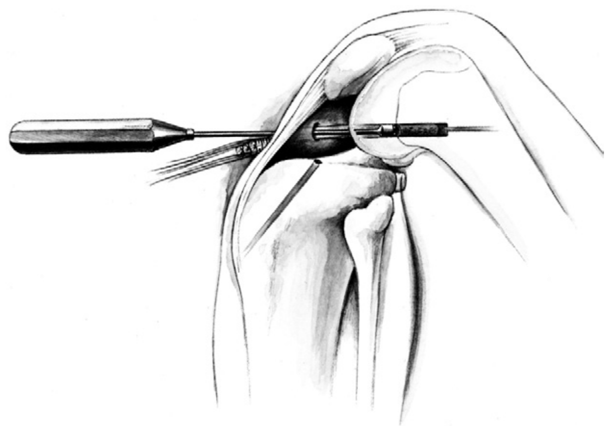

Figure 5. Impact graft bone plug into the femoral tunnel, using an impactor. Place bone plug cortex facing, and parallel with, tibial plateau. By use of a passing suture previously inserted through the Ethibond sutures at the free end, pull graft into the tibial tunnel, twisting the tendon 90° (counterclockwise in right knee, clockwise in left knee) to create AM and PL bundles.

tendons were knotted to form 2 loops with a simple knot. The knots were maximally tightened under cyclic manual load and then secured with U-shaped Ethibond No. 2 sutures. For femoral and tibial tunnel placement, the same fluoroscopic controlled technique was used as for the BPT. First, a femoral tunnel was drilled by use of a drill bit corresponding to the diameter of both loops. A cannulated dilator with the same diameter was introduced 10 mm deep into the femoral tunnel. A K-wire was passed through this dilator until the lateral thigh skin was reached, where a 12-mm stab wound was incised. Then, the K-wire was over-drilled with a drill matching the diameter of the tendon knot, until the dilator was reached. The drill was replaced by an impactor to ensure that no cancellous bone remained in the bottom of this tunnel, thus creating a bottleneck tunnel. The loops were finally pulled from lateral into the femoral bottleneck and the tibial tunnel by use of 4-mm Mersilene tapes (Ethicon) drawn through the graft loops. After cycling of the knee 20 times under maximal manual load, the tapes were fixed on the tibia over a 10-mm cortical bone bridge in 10° of flexion as for the BPT (Fig 7).

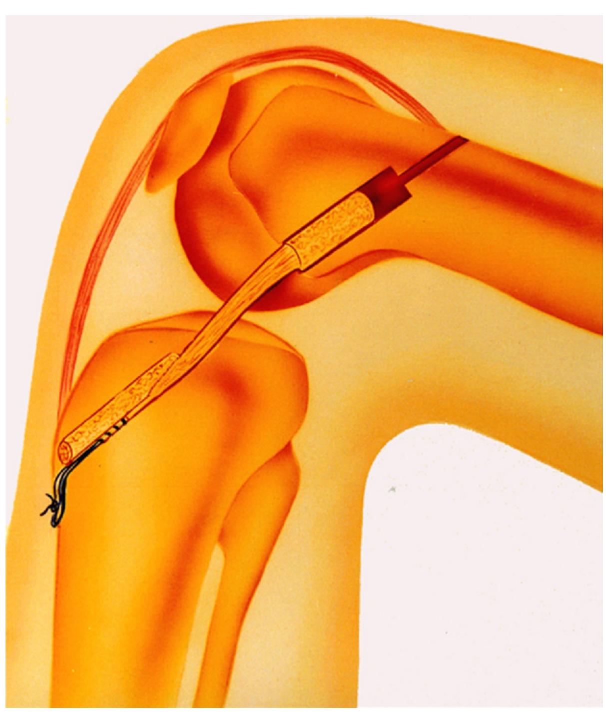

Figure 6. BPT ACL reconstruction: Bone plug press-fit into femoral bone tunnel through AMP; tibial fixation also press-fit with bone plug from femoral tunnel plus fixation over 10-mm bone bridge.

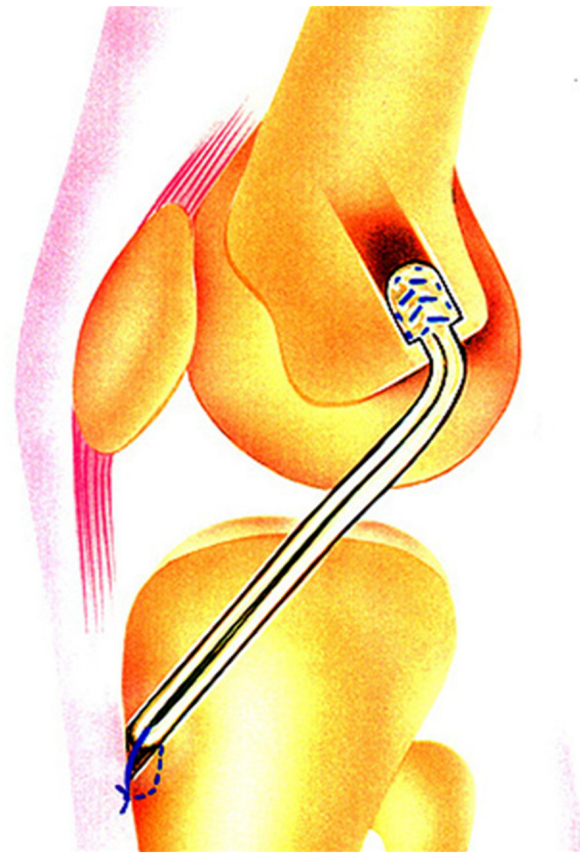

Figure 7. HT ACL reconstruction: The ends of each tendon (semitendinosus and gracilis) are tied to a simple knot, thus creating a bottleneck-like femoral tunnel with the knot contacting the compacta. Tibial fixation is achieved over a cortical bone bridge with nonresorbable sutures.

Rehabilitation

We used the same rehabilitation program for both techniques, which emphasized restoration of full extension and quadriceps function as soon as possible. Immediately after the operation, an accelerated rehabilitation program was initiated. Full weight bearing was encouraged as tolerated. An Aircast Cryo Cuff cooling and compression system (Ormed, Freiburg, Germany) was applied from the first day until swelling was reduced significantly. A brace allowing full hyperflexion (Hypex Light; Albrecht, Neubeuern, Germany) was used for the first 6 weeks. Quadriceps strengthening was restricted to closed kinetic chain exercises during the first 3 months. Proprioceptive training, exercise bicycle use, and aqua jogging were initiated after 3 weeks and continued for 3 months. Jogging was allowed at 3 months postoperatively at the earliest. A minimum period of 6 months was recommended for return to unrestricted athletic activity including pivotal sports such as football or skiing.

Clinical Assessment

All patients were assessed by 2 independent examiners 9 years postoperatively. For subjective evaluation, the Lysholm score, the Tegner score, and a visual analog scale (VAS) for patient satisfaction were used. Clinical results were acquired with the objective International Knee Documentation Committee (IKDC) evaluation form.[5] For assessment of knee stability, the Lachman, anterior drawer, and pivot-shift tests were performed. To gain objective data regarding knee laxity, the side-to-side difference on manual maximum testing was determined with the KT-1000 arthrometer (MEDmetric, San Diego, CA). Range of motion (ROM) was measured with a standard goniometer. For crepitus, all 3 compartments were examined.

To analyze donor-site morbidity including anterior knee pain, kneeling and knee-walking tests were performed.[3,6] Isokinetic testing was done with Lidoactive (LOREDAN Biomedical, Davis, CA). The end position was set at 0° of extension and 90° of flexion, and the angular speed was 60°/s. Finally, the mean of 10 repetitions was compared with the uninjured knee and expressed as a percentage. Further clinical testing included the single-leg hop test. Patient comorbidities including being a smoker and being overweight were analyzed.

Magnetic Resonance Imaging

The status of the articular cartilage and the meniscus morphology was assessed directly by arthroscopy before ACL reconstruction. An MRI scan of the operated and contralateral knee joints was done at the follow-up 9 years postoperatively. T1-weighted sequences in the coronal, sagittal, and individually adjusted (in the direction of the ACL) planes were obtained with a dedicated 0.2-T MRI scanner (C-Scan; Esaote, Genoa, Italy) specifically designed for limbs and joint examination. Images were performed with 3-mm thickness; repetition time was 580 milliseconds, and echo time was 26 milliseconds. All images were analyzed by an independent and blinded radiologist.

For analysis of articular cartilage, we used the International Cartilage Repair Society evaluation package. A maximum of 2 lesions with the highest grades were classified (grades 0 to 4), measured in square millimeters, and assessed according to their location. The number of patients having either 1 or 2 lesions was counted.

Meniscus lesions were classified into 5 grades (0, no lesion; 1, intrameniscal lesion; 2, linear lesion with contact with meniscal surface; 3, complete linear tears; and 4, complex multifragmented tear). Additional data were acquired including Caton-Deschamps Index,[7] measurement of the femoral and tibial tunnel diameter (mean of proximal, middle, and distal value), and sagittal ACL angle set on the tibial plateau.

Statistics

Statistical analysis was performed with the preoperative data and the 1- and 9-year postoperative data. The results of measurements and ordered categorical variables (such as IKDC categories) of both groups at each follow-up time were compared with each other and statistically analyzed with the Student t test for normal variables and the Mann-Whitney U test for non-normal variables. The level of significance was set at $P < .05$ with a confidence interval of 95%. We also assessed clinical changes of the variables over time using the Pillai statistic for both groups together. A lineal regression analysis was performed to compensate for differences that might have existed at the beginning of follow-up. Correlations were done with the Pearson correlation coefficient. A power analysis to determine the number of cases was performed post hoc. Primary outcome measures were the KT-1000 test and the single-leg hop test. All tests were 2-sided, and the level of significance was set at $P < .05$ as usual. The analysis of the needed number of cases was based on a double-sided question: the effect size and the calculation of the number of cases. For the effect size, the α failure and the power were set as usual in medical studies at 5% and 80%, respectively. A computer-based determination of the number of cases was performed with a 2-sample *t* test (Russell V. Lenth, 2001; PI-Face, version 1.51; http://www.stat.uiowa.edu/~rlenth/Power/). Thereby, the measured data were used, and the mean values, as well as the standard deviations, were extracted. The differences in the mean values and the standard deviations of the main criteria described in this report were used to determine the number of cases. Therefore they were integrated post hoc in the computer program (as described previously). The results showed that for the KT-1000 test, 276 patients would be necessary in each group to become significant, and for the single-leg hop test, only 49 patients were necessary in each group to obtain a significant difference with clear advantages for the HT group. All analyses were performed by use of SPSS software, version 15.0 (SPSS, Chicago, IL).

RESULTS

At a mean follow-up of 8.8 years (SD, 0.55 years; range, 7.41 to 10 years), 54 patients were examined, 29 in the BPT group (18 men and 11 women) and 25 in the HT group (15 men and 10 women).

In 6 patients (3 in BPT group and 3 in HT group), ACL rerupture occurred (rerupture rate, 11.1%). Four of these reruptures, two in each group, were caused by a new injury during sports. The mean time between surgery and graft rerupture was 2.44 years. Interestingly, the reruptures in the BPT group occurred earlier (1 year after reconstruction) compared with the HT group (3.86 years). Of 6 patients, 5 had a revision ACL reconstruction. Patients with a rerupture after ACL reconstruction were excluded from the study.

Unfortunately, we lost 8 patients to follow-up (dropout rate, 12.9%). Of these patients, 5 could not be located or moved overseas and 3 refused to attend the follow-up (2 for business reasons and 1 because of unwillingness). The latter 3 patients and the 3 patients who moved overseas were interviewed by phone. All of them were satisfied with their knee function and did not complain about clinical or functional limitations 9 years postoperatively. None of these 6 patients described any problems with activities of daily living, and 4 participated in high-impact sports.

Clinical and Functional Results

Of the patients seen in person, 63.8% were involved in high-impact sports and 34.1% in low-impact sports such as jogging, swimming, or cycling. Only 1 patient (2.1%) reported not performing any sports activity.

The significant difference between BPT and HT observed at 1-year follow-up in the Lysholm score

TABLE 1. *Comparison of Scores in BPT and HT Groups Preoperatively, at 1-Year Follow-up, and at Final Follow-up and Changes in Variables Over Time Using Pillai Statistic for Both Groups Combined*

	BPT (± SEM)	HT (± SEM)	*P* Value (BPT *v* HT)
Lysholm score			
9-yr follow-up	87.28 (± 1.761)	91.82 (± 1.713)	.073
1-yr follow-up	90.87 (± 1.824)	95.61 (± 0.632)	.019*
Preoperatively	65.36 (± 3.315)	65.74 (± 3.122)	.933
Changes over time (Pillai statistic)		$P < .001$*	
Tegner score			
9-yr follow-up	6.20 (± 0.346)	6.14 (± 0.368)	.900
1-yr follow-up	6.61 (± 0.269)	7.06 (± 0.202)	.184
Preoperatively	4.00 (± 0.318)	4.06 (± 0.337)	.890
Changes over time (Pillai statistic)		$P < .001$*	
IKDC score (1-4)			
9-yr follow-up	2.08 (± 0.099)	1.55 (± 0.127)	.002*
1-yr follow-up	1.81 (± 0.157)	1.61 (± 0.120)	.330
Preoperatively	3.32 (± 0.117)	3.35 (± 0.127)	.853
Changes over time (Pillai statistic)		$P < .001$*	
VAS satisfaction score at 9-yr follow-up	8.46 (± 0.231)	9.10 (± 0.177)	.095
Subjective function (side-to-side) at 9-yr follow-up	86.72% (± 2.271%)	92.95% (± 1.992%)	.047*

NOTE. For the IKDC score, 1 indicates normal; 2, nearly normal; 3, abnormal; and 4, severely abnormal. For the VAS and subjective function, results are only available for the 9-year follow-up. The significance level was set at $P < .05$.

Abbreviation: SEM, standard error of the mean.

*Significance.

TABLE 2. *Comparison of Clinical Examination Data in BPT and HT Groups Preoperatively, at 1-Year Follow-up, and at Final Follow-up and Changes in Variables Over Time Using Pillai Statistic for Both Groups Combined*

	BPT (± SEM)	HT (± SEM)	*P* Value (BPT *v* HT)
Lack of extension (side-to-side)			
9-yr follow-up	1.61° (± 0.427)	2.81 (± 0.553°)	.198
1-yr follow-up	<0.01° (± 0.003)	0.32° (± 0.224°)	.161
Preoperatively	0.80° (± 0.374)	0.23° (± 0.227°)	.093
Changes over time (Pillai statistic)		$P = .002$*	
Lack of flexion (side to side)			
9-yr follow-up	1.80° (± 0.757°)	1.14° (± 0.457°)	.472
1-yr follow-up	<0.01° (± 0.001°)	0.65° (± 0.645°)	.325
Preoperatively	6.77° (± 1.948°)	9.10° (± 1.518°)	.745
Changes over time (Pillai statistic)		$P < .001$*	
Lachman test (0-3)			
9-yr follow-up	0.56 (± 0.101)	0.45 (± 0.109)	.481
1-yr follow-up	0.13 (± 0.061)	0.07 (± 0.045)	.399
Preoperatively	1.84 (± 0.094)	1.35 (± 0.087)	<.001*
Changes over time (Pillai statistic)		$P = .001$*	
Anterior drawer test (0-3)			
9-yr follow-up	0.24 (± 0.087)	0.05 (± 0.045)	.056
1-yr follow-up	0.10 (± 0.054)	0.03 (0.032)	.310
Preoperatively	1.74 (± 0.092)	1.39 (± 0.089)	.008*
Changes over time (Pillai statistic)		$P = .001$*	
Pivot shift test (0-3)			
9-yr follow-up	0.28 (± 0.092)	0.18 (± 0.084)	.439
1-yr follow-up	0.06 (± 0.045)	<0.01 (± 0.000)	.156
Preoperatively	1.58 (± 0.101)	1.06 (± 0.103)	.002*
Changes over time (Pillai statistic)		$P < .001$*	
KT-1000 (side-to-side)			
9-yr follow-up	0.90 mm (± 0.271 mm)	0.64 mm (± 0.356)	.553
1-yr follow-up	1.16 mm (± 0.161 mm)	1.06 mm (± 0.146)	.658
Preoperatively	7.84 mm (± 0.489 mm)	6.81 mm (± 0.408 mm)	.110
Changes over time (Pillai statistic)		$P < .001$*	
Patellofemoral crepitus (0-3) at 9-yr follow-up	0.73 (± 0.105)	0.29 (± 0.095)	.003*

NOTE. For patellofemoral crepitus, results are only available for the 9-year follow-up. The significance level was set at $P < .05$.
Abbreviation: SEM, standard error of the mean.
*Significance.

was not seen 9 years after surgery (Table 1). However, there was a significant increase ($P < .001$) compared with the preoperative results. No significant difference was found in the Tegner score at any time of follow-up or between preoperatively and 9 years postoperatively. The VAS analyzing patient satisfaction showed a slightly but not significantly higher result for the HT group (8.46 *v* 9.1) at the 9-year follow-up. However, the subjective function compared with the nonoperated knee was significantly higher for the HT group (86.72% *v* 92.95%, $P = .047$). Both scores were only evaluated at the 9-year follow-up.

The IKDC form showed a significant difference between both groups: 84% patients in the BPT group and 94.4% in the HT group had an IKDC score of A or B, indicating a normal or nearly normal result. No patient had a severely abnormal result (D). The advantage in the HT group was already seen at the 1-year follow-up, but there were fewer patients in the BPT group with normal or nearly normal results (77.5% *v* 96.8%). Both groups were significantly improved ($P < .001$) compared with preoperatively, when 3.2% versus 6.4% had a normal or nearly normal result.

There were no significant differences in the ROM or stability testing between groups (Table 2). No gross pivot shift was seen. KT-1000 manual maximum testing showed a side-to-side difference of less than 3 mm in 95.0% of the BPT patients and 91.7% of the HT patients. Crepitus was observed almost exclusively in the patellofemoral compartment.

The significant difference in kneeling and knee walking between both groups at the 1-year follow-up persisted at the 9-year follow-up. In addition, the

Table 3. *Comparison of Functional Test Data in BPT and HT Groups Preoperatively, at 1-Year Follow-up, and at Final Follow-up and Changes in Variables Over Time Using Pillai Statistic for Both Groups Combined*

	BPT (± SEM)	HT (± SEM)	*P* Value (BPT *v* HT)
Kneeling test (1-4)			
9-yr follow-up	1.48 (± 0.102)	1.09 (± 0.063)	.002*
1-yr follow-up	1.58 (± 0.090)	1.0 (± 0.000)	<.001*
Preoperatively	1.61 (± 0.172)	1.62 (± 0.195)	.999
Changes over time (Pillai statistic)		*P* = .013*	
Knee-walking test (1-4)			
9-yr follow-up	1.72 (± 0.158)	1.14 (± 0.075)	.002*
1-yr follow-up	2.29 (± 0.133)	1.10 (± 0.054)	<.001*
Preoperatively	2.00 (± 0.222)	1.84 (± 0.197)	.161
Changes over time (Pillai statistic)		*P* = .008*	
Single-leg hop test (side to side)			
9-yr follow-up	93.17% (± 2.427%)	99.06% (± 1.660%)	.062
1-yr follow-up	91.05% (± 1.466%)	95.75% (± 1.076%)	.012*
Preoperatively	76.28% (± 7.658%)	78.83% (± 5.740%)	.791
Changes over time (Pillai statistic)		*P* = .013*	
Isokinetic flexion (side to side)			
9-yr follow-up	100.29% (± 3.077%)	95.06% (± 3.312%)	.588
1-yr follow-up	99.14% (± 2.865%)	90.34% (± 1.432%)	.009*
Preoperatively	92.28% (± 5.925%)	80.66% (± 4.173%)	.114
Changes over time (Pillai statistic)		*P* = .042*	
Isokinetic extension (side to side)			
9-yr follow-up	95.98% (± 3.447%)	96.41% (± 1.840%)	.607
1-yr follow-up	86.66% (± 1.886%)	91.90% (± 2.302%)	.084
Preoperatively	83.44% (± 7.979%)	73.49% (± 3.875%)	.267
Changes over time (Pillai statistic)		*P* < .001*	

NOTE. The significance level was set at $P < .05$.
Abbreviation: SEM, standard error of the mean.
*Significance.

single-leg hop test showed an advantage for the HT group. Patients in both groups showed better results compared with the 1-year follow-up and significantly increased results compared with the preoperative status (Table 2).

Group analysis showed persistently lower isokinetic hamstring strength in the HT group at follow-up (Table 3). At the 1-year follow-up, BPT patients showed 99.1% of hamstring strength versus 90.3% in the HT group ($P = .009$). At the 9-year follow-up, the BPT group still presented with higher strength in flexion but no more significant difference. Isokinetic testing of quadriceps muscle function showed no significant differences between groups at the 1-year and 9-year follow-up visits. However, there was a significant improvement of the quadriceps strength especially in the BPT group from 1 to 9 years postoperatively (Table 3). No significant correlation was found between comorbidities such as being a smoker and being overweight and any aspect of clinical or functional results.

MRI Results

Regarding the mean grade of chondral lesion and the mean size of this lesion, the between-group analysis showed no significant difference (Table 4). The overall number of HT patients having grade 3 or 4 chondral lesions of the operated knee and the intact knee was similar. However, in the BPT group a significantly higher number of patients showed a grade 3 or 4 chondral lesion of the operated knee compared with the intact knee (Table 4).

Looking at the development of cartilage status over a period of 9 years, significant deterioration of the degree of chondral lesions was found in both groups (0.83 *v* 2.13 [$P < .001$] for BPT and 0.35 *v* 2.05 [$P = .001$] for HT). For both groups, the most frequent localization of a preoperative chondral lesion was the medial femoral condyle; 9 years postoperatively, it was in the region of the lateral tibial plateau (again for both groups). Comparing the status to the intact contralateral knee at the 9-year follow-up, we found that

Table 4. *Mean Grade and Size of First Chondral Lesion and Percent of Patients With Grade 3 and 4 Cartilage Lesions in Operated and Nonoperated Knee Joints Intraoperatively and at Final Follow-up*

	Mean Grade of First Chondral Lesion Intraoperatively (± SEM)	Mean Grade of First Chondral Lesion at Follow-up (± SEM)			Mean Size of First Chondral Lesion (± SEM) (mm^2)			% of Patients With Grade 3 and 4 Chondral Lesions (%)		
	Operated	Operated	Nonoperated	*P* Value (Operated *v* Nonoperated)	Operated	Nonoperated	*P* Value (Operated *v* Nonoperated)	Operated	Nonoperated	*P* Value (Operated *v* Nonoperated)
BPT	0.8 (± 0.21)	2.1 (± 0.24)	1.4 (± 0.26)	.145	27.2 (± 4.47)	21.1 (± 3.07)	.238	30.4%	13.0%	.040*
HT	0.4 (± 0.17)	2.1 (± 0.28)	1.8 (± 0.29)	.663	36.4 (± 8.28)	30.8 (± 3.55)	.690	35.0%	25.0%	.317
P value (BPT *v* HT)	.085	.825	.293		.301	.049*		.824	.048*	

NOTE. The significance level was set at $P < .05$.
Abbreviation: SEM, standard error of the mean.
*Significance.

the most frequent localization was equally the medial and lateral tibial plateau in the BPT group and again the lateral tibial plateau in the HT group.

No positive correlation was seen between any of the clinical or functional assessment aspects (Lysholm, Tegner, IKDC, KT-1000 difference, hop test) and the grade of chondral lesion.

Similar to the chondral lesion, no significant difference was found in the grade of medial or lateral meniscal lesion or the number of patients having meniscal lesions between the operated and intact knees of both groups at the 9-year follow-up (Table 5). A bicompartmental meniscus lesion occurred with significantly higher frequency in the operated knee compared with the intact knee in both groups (30.4% *v* 13.04% [$P = .04$] for BPT and 40% *v* 5% [$P = .0001$] for HT). Between-group analysis of the operated and intact knee joints showed no significant difference regarding the number of patients having grade 3 or 4 meniscal lesions and the grade of meniscus injuries (Table 5). When we compared both groups, no significant difference was found in the number of patients with unicompartmental and bicompartmental meniscus lesions at follow-up.

No correlation was observed between any of the clinical or functional assessment aspects and the grade or number of patients with medial or lateral meniscal lesion. No patient presented with symptoms of meniscus lesion, yet several cases were detected. Only 1 patient in the cohort (HT group) underwent arthroscopic medial partial meniscectomy at follow-up.

Between-group analysis of the Caton-Deschamps Index at the 9-year follow-up showed no significant difference (BPT 0.927 *v* HT 0.915). There were no significant differences in between-group analysis regarding the development of the tunnel size. At the 9-year follow-up, the mean diameter of the tibial tunnel was significantly increased in size compared with the intraoperative drill diameter (116.02% *v* 115.67%, $P < .001$) but reduced on the femur (88.97% *v* 99.66%, $P = .014$). The sagittal ACL angle to the tibial plateau showed no significant differences between groups (65.1° *v* 65.1°).

DISCUSSION

The aim of this prospective randomized study was to evaluate the long-term results after implant-free ACL reconstruction using BPT versus HT, both with an arthroscopically assisted press-fit technique and with fixation close to the insertion sites. To our knowledge, there is no published study comparing the op-

TABLE 5. *Mean Grade of Meniscal Lesion and Percent of Patients With Medial or Lateral Meniscal Lesions in Operated and Nonoperated Knee Joints at Final Follow-up*

	Mean Grade of Meniscal Lesion (± SEM)			No. of Patients With Grade 3 and 4 Meniscal Lesions (%)		
	Operated	Nonoperated	*P* Value (Operated *v* Nonoperated)	Operated	Nonoperated	*P* Value (Operated *v* Nonoperated)
Medial meniscus						
BPT	1.9 (± 0.32)	1.7 (± 0.28)	.627	43.5%	39.1%	.571
HT	2.3 (± 0.23)	2.0 (± 0.24)	.327	55.0%	30.0%	.093
P value (BPT *v* HT)	.473	.690		.848	.228	
Lateral meniscus						
BPT	1.6 (± 0.30)	1.4 (± 0.29)	.591	30.4%	30.4%	>.999
HT	1.3 (± 0.31)	1.0 (± 0.31)	.461	30.0%	20.0%	.157
P value (BPT *v* HT)	.533	.323		.952	.123	

NOTE. The significance level was set at $P < .05$.
Abbreviation: SEM, standard error of the mean.

erated knee with the intact knee 9 years after ACL reconstruction using clinical, functional assessment as well as bilateral MRI scans.

The strength of this study was its prospective and randomized design. All patients were operated by the same surgeon, who is well experienced in both techniques. The operation techniques were comparable. All patients received the same postoperative management and were clinically examined by 2 independent examiners. All MRI scans were analyzed by an independent and blinded examiner, a certified radiologist, who is well experienced and unaware of the clinical and functional results.

Because of follow-up, we noticed a rerupture rate of 11% with an earlier failure rate in the BPT group; 4 of the 6 reruptures were the consequence of a new sports injury. In an animal study the femoral press-fit fixation technique of the BPT graft showed a similar pullout strength to fixation with interference screws,[8] as well as similar stiffness.[9] In addition, Papageorgiou et al.[10] showed in another animal study that the bone plugs are fully incorporated 6 weeks after operation, so the early failure rate especially in the BPT group should not be a general problem of the implant-free press-fit technique.

An explanation for the high difference of the mean time between surgery and graft rerupture is also the very late detection of 1 of the failures in the HT group at the latest follow-up.

There are only a few reports about press-fit fixation avoiding implants in the literature. The surgical technique of an implant-free knot/press-fit technique described previously[4] has been tested in cadaveric studies. Jagodzinski et al.[11] reported a higher failure load of press-fit fixation with looped semitendinosus and gracilis tendon secured by a tape over a bone bridge compared with interference screw fixation. Kilger et al.[12] found no significant differences in anterior tibial translation comparing the knot/press-fit technique with EndoButton fixation (Ethicon, Somerville, NJ). Boszotta et al.[13] observed a significantly higher primary stability with tibial press-fit bone block fixation of a patellar ligament graft in ovine knee joints compared with titanium interference screws, a titanium staple fixation, or fixation with sutures only over a bone bridge. Hertel et al.[14] reported excellent and good results in more than 80% of patients after BPTB press-fit fixation at 10 years' follow-up.

The appropriate graft choice is still discussed controversially. Numerous studies document good clinical results with the use of BPTB and HT autografts.[2,15] Although several prospective randomized short- and medium-term studies have been published,[16-20] only a few randomized long-term studies can be found in the literature.[21-23] Ten-year results comparing the outcome after BPTB and HT ACL reconstruction have been published by Pinczewski et al.[3] in a prospective nonrandomized trial. They described similar results between both groups.

Several studies have described lower donor-site morbidity when using HT compared with patellar tendon for ACL reconstruction.[2,3,15,18,24] In our study we also noticed significantly lower anterior knee pain in the HT group compared with the BPT group.

Hertel et al.[14] found similar results for the Lysholm score, Tegner score, and VAS. Long-term studies by

Pinczewski et al.[3] and Lidén et al.[23] also did not find any difference regarding Lysholm score and sports activity between patients after BPTB or HT ACL reconstruction. Several other prospective studies have confirmed these findings.[17,20,25,26]

In the 1970s and 1980s loss of ROM and especially loss of extension were major concerns after ACL reconstruction. Fixed flexion deformities ranging from 10°[27] to 24°[28] have been described. Recent studies still report the occurrence of fixed flexion deformities after ACL surgery. Anderson et al.[29] reported a loss of knee extension ranging from 3° to 10° in 11 patients and a loss of knee flexion ranging from 6° to 33° in 11 out of 105 patients. In contrast, Pinczewski et al.[3] and Lidén et al.[23] found no significant difference in ROM between operated and intact knees at long-term follow-up.

Several studies observed similar results for KT-1000 side-to-side difference between BPTB and HT patients.[3,23,30] However, Keays et al.[30] stated that a significant difference was found when comparing BPTB and HT patients with intact knees in a control group. They concluded that normal preinjury stability cannot be restored irrespective of the type of graft. In our study both autografts produced good stability without significant signs of early anterior or rotational laxity. This may be because of precise and anatomic tibial and femoral tunnel placement as well as a nearly anatomic ACL angle.

There are only a few long-term studies comparing quadriceps and hamstring strength after ACL reconstruction with BPTB or HT using isokinetic testing methods. Keays et al.[30] assessed similar results for both groups 6 years postoperatively. BPTB patients continued to have a 6% deficit in quadriceps strength of the operated knee at 60°/s, and HT strength deficit was 3% both at 60°/s and at 120°/s compared with the contralateral intact knee.

No significant difference in hamstring and quadriceps strength was measured in our study. The permanent loss of nearly 5% of hamstring strength did not influence the functional hop test or the return to the preinjury sports level. In contrast, HT patients had significantly better results for the hop tests at the 1-year follow-up and still better results at the 9-year follow-up. However, we have not performed a test for deep flexion strength looking for a specific morbidity of the HT group.

A limitation of this study is the use of the dedicated low-field MRI. Riel et al.[31] found a fair to very good sensitivity, specificity, and accuracy when analyzing the meniscus and the cruciate ligaments but a lower sensitivity when analyzing the cartilage status (72%). However, they found a very good specificity (100%) and accuracy (92%). For the diagnosis of meniscal tears, Franklin et al.[32] found an equal or even better specificity and sensitivity using a dedicated MRI scanner rather than described in prior studies using a high-field MRI. In contrast, Kladny et al.[33] described a lower sensitivity using low-field MRI analyzing meniscal tears. They also found no difference analyzing cartilage degeneration grades 0 through 3, but they described that in 5 of 6 cases of grade 4 lesions, they could not be found on the low-field MRI scan. Interestingly, Riel et al. found a disadvantage of low-field MRI in overlooking the low-grade lesions but reliable detection of high-grade lesions. In addition, Ahn et al.[34] could show in a cadaveric study comparing low-field MRI with anatomic morphologies that higher lesions could be detected effectively. Certainly, the use of high-field MRI with 1.5 to 3 T or ultrahigh-field MRI has advantages in detection of cartilage defects. Admittedly, in 2009 Krampla et al.[35] examined the influence between field strength (1, 1.5, and 3 T) and the radiologist's experience. They found that even for well-experienced radiologists, the technical superiority of a 3-T high-field MRI scan did not lead to an increase in sensitivity or specificity. So the deployment of dedicated low-field MRI used in our study should be an adequate method to analyze the knee joint because a well-experienced radiologist evaluated the images. Small limitations are present in the analysis of the cartilage status, but the higher lesions especially should be detected in a satisfactory manner.

It is well-known that patients with acute ACL injuries may have associated chondral and meniscal damage.[36,37] Increased radiologic evidence of joint degeneration and increased disability, pain, and swelling have been noted to develop in patients managed nonoperatively.[38,39] Multiple studies have analyzed the incidence of osteoarthritic changes in the knee in the long-term using radiographs. Because there is no prospective randomized long-term study using MRI for this purpose, our results may only be compared with radiologic findings.

Pinczewski et al.[3] reported a significantly higher incidence of radiographic arthritic changes in the BPTB group compared with the HT group in their long-term prospective study. The findings have been consistent with early studies of the same patient cohort.[40] In a midterm study Keays et al.[30] found a significantly higher incidence of tibiofemoral osteoarthritis in the BPTB group (62% *v* 33%).

In contrast, similar results regarding the grade of cartilage and meniscus lesions were found in our study between groups. Moreover, there was no significant difference when the operated knee was compared with the contralateral intact knee, indicating that a stable knee joint may prevent the knee from the development of chondral and meniscal lesions.

Shelbourne and Gray[41] examined the outcome of 502 BPTB patients with a special interest in interference of ROM with functional and radiologic results. They found a significantly higher prevalence of osteoarthritic changes in patients having a significant loss of motion. In contrast, Pinczewski et al.[3] did not find any correlation between loss of extension and poorer radiographic findings in the BPTB and HT groups. In our study there was also no correlation between meniscal and chondral MRI changes and any aspect of subjective, clinical, and functional assessment of patients. However, a small deterioration of the chondral status was seen compared with the intraoperative status. This may be due to the process of normal aging, especially given that there was no difference compared with the contralateral intact knee joint.

Potential limitations of the study include the comparatively low number of patients, the relatively high dropout rate, and the missing control group. There are no preoperative or 1-year follow-up MRI data, and the MRI results obtained 9 years postoperatively were compared with the intraoperative chondral and meniscal status. The use of the dedicated low-field MRI scanner could be a matter of controversy. In addition, we had no previous MRI data on the contralateral intact knee, so we had no possibility of comparing the current status with previous findings.

CONCLUSIONS

The implant-free press-fit technique for anterior cruciate ligament reconstruction using bone–patellar tendon and hamstring grafts with anatomic graft placement is an innovative technique to preserve the cartilage and meniscal status without significant differences between the operated and nonoperated knees in the long term. Significantly less pain was noted in the hamstring group, when testing for kneeling and knee walking.

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