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Tunnel widening after ACL reconstruction with aperture screw fixation or all-inside reconstruction with suspensory cortical button fixation☆

Volumetric measurements on CT and MRI scans

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ABSTRACT

Background: Tunnel widening after anterior cruciate ligament reconstruction (ACLR) is influenced by the surgical and fixation techniques used. Computed tomography (CT) is the most accurate image modality for assessing tunnel widening, but magnetic resonance imaging (MRI) might also be reliable for tunnel volume measurements. In the present study tunnel widening after ACLR using biodegradable interference screw fixation was compared with all-inside ACLR using button fixation, with tunnel volume changes being measured on CT and MRI scans.

Study design: Randomized controlled trial; Level of evidence, 2.

Methods: Thirty-three patients were randomly assigned to hamstring ACLR using a biodegradable interference screw or all-inside cortical button fixation. CT and MRI scanning were done at the time of surgery and six months after. Tunnel volume changes were calculated and compared.

Results: On CT, femoral tunnel volumes changed from the postoperative state (100%) to 119.8% with screw fixation and 143.2% with button fixation ($P = 0.023$). The changes in tibial tunnel volumes were not significant (113.9% vs. 117.7%). The changes in bone tunnel volume measured on MRI were comparable with those on CT only for tunnels with interference screws. Tibial tunnels with button fixation were significantly underestimated on MRI scanning ($P = 0.018$).

Conclusions: All-inside ACLR using cortical button fixation results in increased femoral tunnel widening in comparison with ACLR with biodegradable interference screw fixation. MRI represents a reliable imaging modality for future studies investigating tunnel widening with interference screw fixation.

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1. Introduction

Failure of graft incorporation and the development of tunnel widening (TW) after anterior cruciate ligament (ACL) reconstruction have been frequently reported in the literature [1–6]. Although there appears to be no correlation between TW and clinical outcome measures [5,7,8], it is widely accepted that TW potentially complicates ACL revision surgery. Excessive TW might first require bone tunnel filling, with ACL reconstruction following at a second stage.

The incidence of tunnel widening of more than two millimeters when an autogenous hamstring graft is used ranges from 17% to 41% [2,4,9]. The etiology of TW is still not fully understood, and it may be multifactorial, including mechanical and biological factors [1,2,10]. It has been postulated that graft micromotion within the tunnels on the longitudinal axis (the “bungee cord effect”) and transverse axis (the “windshield wiper effect”) may cause TW [11,12].

The initial fixation must be secure enough to hold the graft in position during biologic incorporation. ACL graft fixation can be divided into two key types: aperture fixation (interference screw and cross-pins) and extra-articular fixation (cortical fixation devices, femoral loops, and tibial cortical fixation). The tunnels enlarge during the insertion of interference screws, followed by further enlargement up to six months and then stabilization [13]. When anatomic ACL reconstruction is carried out with aperture fixation using bioabsorbable interference screws, significant tunnel widening on the femoral and tibial sides has also been reported [14].

All-inside ACL reconstruction allows cortical fixation using adjustable-length loop buttons on both the femoral and tibial sides [15]. Shorter tibial tunnels are created using a retrograde drilling technique, leaving a tibial cortical bridge for button fixation. Cortical button fixation avoids the need to have additional material within the tunnel and allows graft-to-bone contact throughout the whole tunnel. However, this fixation method may result in increased graft lengthening and increased graft micromotion at the tunnel aperture [11,16].

Postoperative tunnel widening can be detected using computed tomography (CT), magnetic resonance imaging (MRI), and radiography. CT scans are the most accurate imaging modality for quantifying bone tunnel changes [17]. The imaging modalities have in the past been evaluated using two-dimensional analysis, although with CT and MRI it is also possible to calculate the three-dimensional volume of bone tunnels. ACL tunnel volume change measured on CT scans has been recently reported in the literature [3,18]. Measuring changes in the tunnel volume using MRI might be reliable and might make it possible to avoid radiation exposure during future research investigations.

The aim of the present study was to assess postoperative change of tunnel volume on CT and MRI scans after ACL reconstruction with biodegradable interference screw fixation and all-inside ACL reconstruction using button fixation. It was hypothesized, firstly, that ACL reconstruction using interference screw fixation results in less bone tunnel widening in comparison with all-inside ACL reconstruction using cortical button fixation. Secondly, it was further hypothesized that tunnel volume changes measured on MRI are comparable with those on CT.

2. Methods

2.1. Patients

CT and MRI data were analyzed for 33 patients enrolled in a prospective randomized controlled trial from 2013 to 2015. Patients were randomly allocated to one of two different hamstring ACL reconstruction and fixation technique groups with an equal probability of allocation. The randomization occurred prior to surgery with given written informed consent. Block randomization was used to assign eligible patients to the treatment arms in order to avoid serious imbalance in the number of participants assigned to each group. In order to maintain allocation concealment, the pattern of the blocks was kept confidential. The subinvestigators were not involved in preparing the randomization list. In the first group, 16 patients underwent ACL reconstruction with conventional tibial tunnel drilling and graft fixation using a biodegradable interference screw on both the femoral and tibial sides. In the second group, 17 patients were treated with all-inside ACL reconstruction using adjustable-length loop button fixation on both the femoral and tibial sides. Patients aged 18–45 were included when they met the following criteria: (1) unilateral ACL rupture diagnosed clinically and on MRI; (2) time interval between ACL injury and reconstruction of one year; (3) Tegner activity score ≥5; and (4) a normal contralateral knee. Major exclusion criteria were total collateral ligament rupture, a full-thickness cartilage lesion visualized on MRI, and an unstable longitudinal meniscus tear (requiring meniscus refixation and changes in the postoperative rehabilitation protocol). From 2013 to 2015, 76 patients were screened for eligibility to participate for the study, 30 did not meet initial inclusion criteria. Forty-six patients were included into the study. Of these, five patients required meniscus refixation intraoperatively with change of the rehabilitation protocol, intraoperative problems in three patients (one femoral button loop rupture, one femoral button mislocation, one femoral screw breakage), three patients sustained early rupture of the ACL graft within six months postoperatively (all-inside ACL reconstruction with button fixation), and two patients denied to come to follow-up visit. In one patient with all-inside ACL reconstruction with button fixation, septic arthritis was suspected two weeks after surgery and the patient was treated with two arthroscopic irrigations with graft retention.

CT and MRI data taken at time zero (within three days after surgery) and after six months were used to calculate tunnel volumes. The study protocol was reviewed and approved by the local hospital ethics committee.

2.2. Surgical technique

2.2.1. Screw fixation

The semitendinosus and gracilis tendons were harvested. The four free ends were whip-stitched using nonresorbable high-strength suture material (FiberWire # 2; Arthrex Inc., Naples, Florida, USA). The tendons were folded to obtain a four-stranded graft. Femoral tunnels 25 mm long were drilled in the center of the femoral ACL insertion through the anteromedial portal at 120° of flexion. Tibial tunnels were created at the ACL footprint using a drill guide fixed at 55°. The tibial stump was preserved. The tunnel size was adapted to the cross-sectional diameter of the graft. The graft was pulled transtibially into the femoral socket. The femoral tunnel aperture was notched, and a 23-mm long biodegradable interference screw (BioComposite; Arthrex Inc.) was inserted over a guide wire. The graft was preconditioned by passive cycling of the knee joint approximately 10 times. A guide wire was placed in the tibial tunnel at the dorsal tunnel wall, eccentrically to the graft. The biodegradable interference screw (BioComposite, Arthrex Inc.), with a length of 23–28 mm, was inserted into the articular tunnel aperture using the length scale on the screwdriver. The screw diameter was selected at one millimeter less than the diameter of the femoral tunnel and one millimeter larger than the diameter of the tibial tunnel. Graft tensioning and tibial graft fixation were carried out at 30° of knee flexion. The mean graft size was 8.2 mm and 7.3 mm on the tibial and femoral sides, respectively.

2.2.2. Button fixation

The semitendinosus tendon was harvested. The tendon was symmetrically folded over two loops of the adjustable-length loop cortical button device (TightRope RT; Arthrex Inc.) in order to obtain a four-stranded graft 60–75 mm in length. The graft was secured with two sutures at the tibial end and two sutures at the femoral end of the graft (FiberWire # 2; Arthrex Inc.) [15]. The socket size was adapted to the cross-sectional diameter of the graft. A femoral socket with a length of 25 mm was created at the anatomic ACL insertion site. Femoral tunnel drilling was performed using the anteromedial (AM) portal reaming technique in seven patients, and with an outside-in technique using a retrograde drilling guide pin in 10 patients (FlipCutter; Arthrex Inc.). The tibial socket was created at the ACL footprint using an ACL drill guide fixed at 55°. The tibial stump was preserved. Using a retrograde drilling guide pin (FlipCutter; Arthrex Inc.), a tibial socket was created, leaving at least a seven-millimeter cortical bridge. The graft was inserted through the AM portal and retrieved into the bone sockets by shortening the adjustable-length loop sutures of the button devices. The graft was preconditioned by passive cycling of the knee joint approximately 10 times, and final graft tension was applied at 30° of flexion. The mean graft size was 8.2 mm and 7.9 mm on the tibial and femoral sides, respectively.

2.2.3. Rehabilitation

From the first postoperative day, all patients performed active quadriceps exercise and passive knee motion, and full weight-bearing was immediately allowed. A knee brace was worn for two weeks postoperatively. From week 4 to 12 cycling, muscle training and swimming were performed. Running was allowed after 12 weeks. Full exercise activity was allowed after six to nine months.

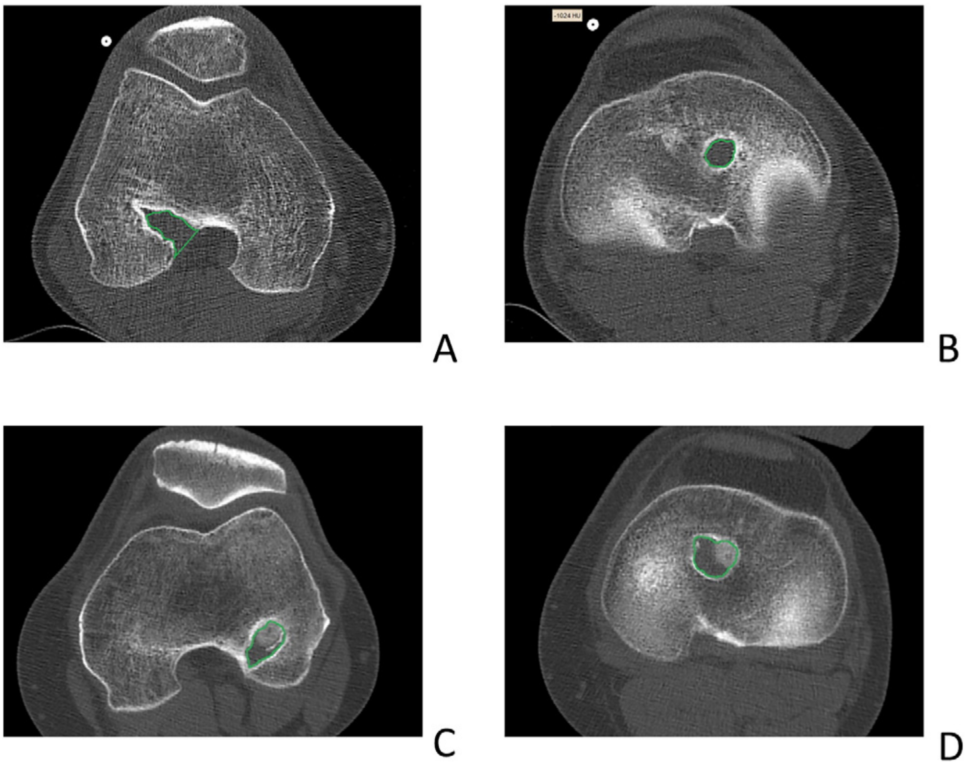

Figure 1. Measurement method of bone tunnel volumes on CT scans shown on exemplary images at six months of follow-up. The cross sectional area of the femoral and tibial bone tunnel with button (A, B) or screw fixation (C, D) was marked on axial CT slices.

2.3. Tunnel volume measurement

2.3.1. CT evaluation

Multidetector CT scanning (GE Discovery CT 750 HD; GE Healthcare, Chicago, Illinois, USA) was performed on the operated knee. The slice thickness was 0.625 mm (512 × 512 voxels). Images were acquired at 100 kV and 120–400 mAs, with a noise index of 25.

The bone tunnel volume was measured on the axial slices (Figure 1). In the group with interference screw fixation, the screw volume was included in the measurement. The cross-sectional area of the bone tunnel was added up and multiplied to calculate the total volume on every third slice (AW Server 2.0; GE Healthcare).

2.3.2. MRI evaluation

Magnetic resonance imaging was performed on a 1.5-T whole-body MR system (Magnetom Avanto; Siemens Healthcare Ltd., Erlangen, Germany) together with a 15-channel extremity coil. Turbo spin echo (TSE) T1 axial slices with a thickness of 3.0 mm were used to measure the volume of the bone tunnel. The cross-sectional area was marked on every axial slice (Figure 2). The bone tunnel volume was calculated in the same way as described above.

Measurements were performed by three observers (R.M., A.R., C.K.). Changes in the tunnel volume between the two time points were defined as tunnel widening and expressed in cubic millimeters and percentages. The mean values from all three observers were used in the analyses.

2.4. Tunnel diameter measurement

CT images were used for tunnel diameter measurements. Images were orientated along the longitudinal axis of the femoral and tibial tunnel. The maximal tunnel diameter of the tunnel was measured.

2.5. Sample size assessment

An effect size of 1.0 when comparing changes in tunnel volume between the two fixation groups was deemed relevant. To achieve this with a power of 80% using a two-group *t*-test with a two-sided significance level of $P < 0.05$, a sample size of 17 in each treatment group is required. The group with screw fixation consisted of 16 patients, but the impact on the statistical power should be negligible, as the effect sizes were mostly greater than originally assumed.

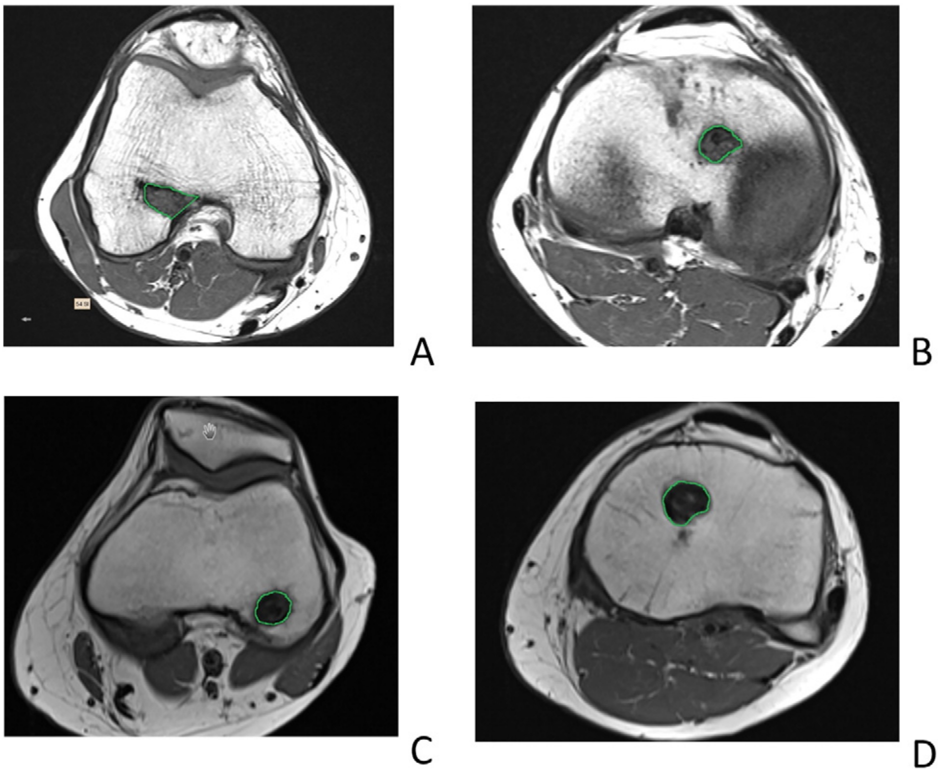

Figure 2. Measurement method of bone tunnel volumes on MRI shown at six months of follow-up of the same patients (Figure 1). The cross sectional area of the femoral and tibial bone tunnel with button (A, B) or screw fixation (C, D) was marked on axial MRI slices.

2.6. Statistical analysis

Statistical analysis was performed using IBM SPSS Statistics for Windows, version 23.0 (IBM Corporation, Armonk, New York, USA). Parametric data are presented as means with standard deviation (SD). The Kolmogorov–Smirnov test was used to check whether the data were normally distributed. Changes in tunnel volume and diameter are presented in percentages as mean with SD. Changes in the tunnel volume were compared between the two study groups using Student's *t*-test. Changes in the tunnel volume measured for the two modalities (CT and MRI) were compared using two-way analysis of variance (ANOVA) with repeated measures. To account for possible sphericity violation among states, the *P* values were corrected in accordance with the Greenhouse–Geisser method [19].

To assess the reliability of the assessments, interrater correlation coefficients (ICCs) for two-way mixed measures were calculated. Reliability was classified, in accordance with Landis and Koch [20], as: 0.0–0.2 poor, 0.21–0.40 fair, 0.41–0.60 moderate, 0.61–0.80 substantial, and 0.81–1.00 almost perfect. The significance level was set at $P < 0.05$.

3. Results

There was no significant difference between the two groups for mean age at time of operation ($P = 0.207$), body mass index (BMI) ($P = 0.915$), Tegner score ($P = 0.593$) and sex ratio ($P = 1.000$) (Table 1).

3.1. Screw vs. button fixation: tunnel volumes

3.1.1. CT scan

In the group with screw fixation, the bone tunnel enlarged to 113.9 ± 10.3% on the tibial side and 119.8 ± 19.2% on the femoral side. In the group with button fixation, the bone tunnel enlarged to 117.7 ± 24.1% on the tibial side and 143.2 ± 34.4% on the femoral side. The differences in tibial tunnel enlargement were not significant ($P = 0.565$). The differences in femoral tunnel enlargement were significant ($P = 0.023$) (Table 2).

3.1.2. MRI scan

In the group with screw fixation, the bone tunnel enlarged to 108.0 ± 14.9% on the tibial side and 110.9 ± 20.7% on the femoral side. In the group with button fixation, the bone tunnel changed to 96.4 ± 19.0% on the tibial side and 154.3 ± 38.0% on the femoral side. The differences between the two groups with regard to tibial tunnel enlargement were not significant ($P = 0.06$). The differences in femoral tunnel enlargement were significant ($P < 0.001$) (Table 2).

No significant differences in the femoral tunnel volume changes were noted when tunnels were drilled using the medial portal drilling or outside-in technique for the group with button fixation (CT: 156.2 ± 35.5% vs. 134.1 ± 34.2%, $P = 0.201$; MRI: 155.7 ± 45.3% vs. 134.1 ± 34.2%, $P = 0.903$). However, it should be noted that this statistical analysis is underpowered.

3.2. Screw vs. button fixation: tunnel diameter

The maximal diameter of the tibial tunnel was significantly larger in the group with screw fixation at time zero and after six months ($P < 0.001$). The femoral tunnel was significantly larger in the group with screw fixation at time zero, however, after six months femoral tunnel diameters were comparable between the two groups ($P = 0.755$) (Table 3). In the group with screw fixation, the bone tunnel enlarged to 111.1 ± 10.8% on the tibial side and 121.3 ± 17.6% on the femoral side. In the group with button fixation, the bone tunnel enlarged to 122.4 ± 9.3% on the tibial side and 143.0 ± 24.2% on the femoral side. The differences in tibial and femoral tunnel widening were significant ($P = 0.003$, $P = 0.006$) (Table 3).

3.3. CT vs. MRI

Table 4 shows the interrater reliability data for the single measurements.

Table 1
Baseline data for a prospective collective of patients with ACL reconstruction with interference screw fixation or all-inside reconstruction using cortical button fixation[a].

	Screw fixation (n = 16)	Button fixation (n = 17)	*P*-value
Age (y)	29 ± 7	26 ± 6	0.207
Sex (m,f)			
Female	4 (25%)	5 (30%)	1.000
Male	12 (75%)	12 (70%)	
BMI	24.1 ± 2.0	24.2 ± 4.5	0.915
Tegner	6.8 ± 1.0	6.9 ± 1.0	0.593

[a] Data are shown as means with standard deviation, n (%). BMI, body mass index.

Table 2
Results for anterior cruciate ligament tunnel volume and volume change[a].

Modality	Group	Tibial tunnel (mm^3)		Femoral tunnel (mm^3)		Tibial tunnel change (%)	Femoral tunnel change (%)
		Postoperative	6 months	Postoperative	6 months		
CT	Screw	2.57 ± 0.50	2.92 ± 0.64	1.17 ± 0.16	1.41 ± 0.35	113.9 ± 10.3	119.8 ± 19.2
	Button	1.07 ± 0.26	1.27 ± 0.44	1.02 ± 0.33	1.43 ± 0.45	117.7 ± 24.1	143.2 ± 34.4
	P	<0.001	<0.001	0.120	0.933	0.565	0.023
MRI	Screw	3.06 ± 0.62	3.33 ± 0.98	1.56 ± 0.28	1.73 ± 0.49	108.0 ± 14.9	110.9 ± 20.7
	Button	1.73 ± 0.33	1.65 ± 0.41	1.30 ± 0.34	1.93 ± 0.45	96.4 ± 19.0	154.3 ± 38.0
	P	<0.001	<0.001	0.026	0.240	0.060	<0.001

[a] Data are shown as means with standard deviation. CT, computed tomography; MRI, magnetic resonance imaging.

Tibial tunnel volume measurements with an interference screw resulted in almost perfect interrater reliability for both CT and MRI. Femoral tunnel volume measurements showed almost perfect agreement with button fixation on CT scanning. All other measurements showed substantial agreement.

The absolute values for tunnel volume were higher on the MRI measurements in comparison with CT scans in both fixation groups. The tibial tunnel volumes showed a trend toward higher values with screw fixation and were significantly higher for the group with button fixation (screw $P = 0.068$, button $P < 0.001$). On the femoral side, this difference was significant in both fixation groups (screw $P = 0.03$, button $P = 0.03$).

The tunnel changes measured on the femoral and tibial sides were comparable for CT and MRI in the group with screw fixation ($P = 0.551$, $P = 0.610$). In the group with button fixation, the tunnel changes measured on MRI showed a trend toward overestimation on the femoral side and were significantly underestimated on the tibial side in comparison with tunnel changes on CT scanning ($P = 0.078$, $P = 0.018$).

4. Discussion

In the present study, bone tunnel volumes were measured after conventional ACL reconstruction with interference screw fixation and all-inside ACL reconstruction using cortical button fixation. The first hypothesis was accepted, as more femoral tunnel widening was observed with button fixation than with screw fixation. The second hypothesis was partially accepted, as CT and MRI showed comparable results for the group with screw fixation only.

Although most studies investigating TW have shown no correlation with the clinical results [1,5,7], some studies have reported inferior stability results for patients in whom more TW was observed [14,21]. In revision surgery, enlarged tunnels may complicate tunnel drilling, and several studies aimed at avoiding TW have been performed. The etiology of TW appears to be multifactorial, involving mechanical factors, the immune response, and cell necrosis within the tunnel [6,22]. Graft fixation influences mechanical factors such as micromotion between the graft and tunnel wall. Rodeo et al. [11], in a study measuring graft micromotion in a rabbit ACL reconstruction, found that graft–tunnel motion impaired graft incorporation, leading to femoral TW at the aperture. Graft–tunnel movements might be reduced with aperture fixation using interference screws. However, the same levels of TW have been reported for metal and biodegradable interference screws composed of poly L-lactic acid (PLLA) [23,24]. The addition of osteoconductive material such as hydroxyapatite (HA) or β-tricalcium phosphate (β-TCP) is thought to enhance screw resorption and bone ingrowth. BioComposite β-TCP/PLLA (30% β-TCP and 70% PLLA) screws were used in the present study. Ntagiopoulos et al. [25] recently reported that β-TCP/PLLA screws were fully resorbed and osteointegrated within four years postoperatively.

In the present study, all-inside ACL reconstruction using cortical button fixation was associated with significantly more femoral TW in comparison with ACL reconstruction using screw fixation. However, femoral tunnel volumes after six months were comparable between the two groups (screw/button: 1.41 vs. 1.43 mm^3). On the tibial side, TW was not significantly different between the two groups. Tibial tunnels after six months were larger with screw fixation due to full tunnel drilling and screw insertion in this group (screw/button: 2.92 vs. 1.27 mm^3). In revision surgery, a comparable tunnel situation after screw or button fixation can be expected on the femoral side, with larger tunnels on the tibial side after screw fixation.

Table 3
Results for anterior cruciate ligament maximum tunnel diameter and widening[a].

Modality	Group	Tibial tunnel (mm)		Femoral tunnel (mm)		Tibial tunnel widening (%)	Femoral tunnel widening (%)
		Postoperative	6 months	Postoperative	6 months		
CT	Screw	11.02 ± 0.83	12.23 ± 1.31	9.13 ± 0.69	11.00 ± 1.20	111.1 ± 10.8	121.3 ± 17.6
	Button	8.29 ± 0.51	10.15 ± 0.94	7.92 ± 1.08	11.15 ± 1.46	122.4 ± 9.3	143.0 ± 24.2
	P	<0.001	<0.001	<0.001	0.755	0.003	0.006

[a] Data are shown as means with standard deviation. CT, computed tomography.

Table 4
Interrater reliability for single measures, expressed as ICCs (three observers).

Modality	Group	Tibial tunnel (mm^3)		Femoral tunnel (mm^3)	
		Postoperative	6 months	Postoperative	6 months
CT	Screw	0.922	0.903	0.606	0.749
	Button	0.762	0.782	0.894	0.902
MRI	Screw	0.869	0.920	0.731	0.780
	Button	0.656	0.796	0.714	0.690

In a randomized controlled trial, Fauno and Kaalund [2] compared the development of TW after ACL reconstruction using either close-to-the-joint fixation (transfemoral pin and tibial interference screw) or extracortical fixation (femoral button and tibial bicortical screw and washer). They reported significantly more femoral and tibial TW in the group with fixation far from the joint. Sabat et al. [4] observed significantly greater femoral TW with cortical button fixation in comparison with transfemoral pin fixation. The results of the present study support the assumption that the site of graft fixation continues to be a major factor in the development of TW after ACL reconstruction.

Marchant et al. [17] assessed the interobserver and intraobserver reliability of measurements of tunnel diameter and cross-sectional area in enlarged bone tunnels on radiographs, CTs, and MRIs. The widest distances on the coronal and sagittal views were measured by five investigators. Only CT scanning showed a high level of interobserver and intraobserver reliability. The authors state that MRI is not reliable even for identifying the presence of a tunnel.

Recent studies have reported on TW using three-dimensional CT scans to calculate the tunnel volume [3,18]. Hwang et al. [3] found no significant difference in femoral tunnel volume change after one year between hamstring grafts inserted in press-fit technique (0.5 mm underdrilled tunnels) and conventional femoral technique (same-sized graft and tunnel) using transfemoral pin fixation in both groups (165% vs. 171.5%). A possible explanation for the increased femoral tunnel volume change compared with our findings (143.2% using the all-inside reconstruction technique) could be the transtibial drilling technique used by Hwang et al. [3]. Araki et al. [18] analyzed bone tunnel volume change after hamstring double-bundle ACL reconstruction in 11 patients using cortical button fixation at the femur and cancellous screw with washer fixation at the tibia. The femoral tunnel volume of the AM and posterolateral (PL) bundle changed to 122.3 ± 31.8 and $112.5 \pm 34.4\%$ at the articular side. The tibial tunnel volume of the AM and PL bundle changed to 108.6 ± 28.7 and $105.4 \pm 22.6\%$ at the articular side. The articular outlet of the femoral and tibial tunnels moved in the direction that the grafts were pulled. Micro-motions and stress of the two bundles against the tunnel wall during knee motion could lead to those transpositions of the centroids in each bone tunnel.

To the best of the present authors' knowledge, this is the first study in which tunnel volume measurements have been carried out on MRI. The volume measurements showed a substantial and almost perfect level of interobserver reliability between the three observers for CT and MRI measurements of tibial and femoral tunnels with and without interference screws. The tunnel volume change measured on MRI was comparable with the volume change measured on CT scans for tunnels with interference screws. MRI volume measurements therefore represent an appropriate modality for use in future research on tunnel widening when biodegradable interference screws are used. In the present study, the tibial tunnel with button showed narrowing on MRI after six months (96%), while CT scans showed tibial tunnel widening (118%). Tunnel volume changes measured on MRI therefore need to be interpreted cautiously if an interference screw is not used, since contradictory results may even appear.

The present study has some limitations. It compared two ACL reconstruction techniques that differ with regard to graft preparation and fixation. Differences in tunnel changes cannot be explained by the two fixation techniques alone, and other influencing factors have to be taken into account. The all-inside graft preparation technique requires more suture material in the femoral and tibial tunnel, which might inhibit tendon-to-bone healing [26,27]. The lengths of the tibial tunnel sizes differed between the two groups, as a full tunnel was drilled for screw fixation and a shorter socket was created for button fixation.

The femoral tunnel drilling techniques were not consistent in the present study. This might lead to a potential confounding factor, with a different femoral tunnel angle and forces acting on the ACL. Angulation of the femoral tunnel has been reported to affect femoral TW. Xu et al. [8] reported significantly more femoral TW with a more vertical and posterior tunnel position drilled transtibially, in comparison with medial portal drilling. In the present study, outside-in femoral tunnel drilling was carried out in 10 patients with button fixation. In all other patients, the femoral tunnels were created by medial portal drilling. The increased femoral TW in the group with button fixation cannot be explained by the outside-in femoral tunnel drilling, as the latter was associated with less femoral tunnel widening in this group.

In the present study, TW was assessed using the total volume change, and tunnel shapes were not analyzed. The location of the main TW might provide additional information about the etiology of TW.

The follow-up period was six months, and TW after that period was not reported. However, Fink et al. and Harris et al. reported that most tunnel enlargement occurs within the first six weeks after surgery [1,28]. In a longitudinal MRI study, Webster et al. [5] reported on TW with patellar tendon and hamstring grafts with interference screw fixation. The tunnels generally increased in size up to six months postoperatively, and decreased slightly after one year. TW occurring after six months may be due to poor graft incorporation and may affect knee stability and involve a risk of repeat rupture. As the clinical outcome was not reported, the influence of TW on the clinical outcome is still unknown in the present study population.

In summary, all-inside ACL reconstruction using adjustable-length loop cortical button fixation was found to be associated with greater femoral tunnel volume enlargement in comparison with full tibial tunnel ACL reconstruction with biodegradable interference screw fixation. Tibial tunnel volume was smaller after all-inside ACL reconstruction and tunnel volume enlargement was not different between the two groups at the tibial side. The results of the present study support the use of MRI to quantify tunnel volume changes in ACL tunnels with interference screws.

Conflicts of interest

All authors declare that they have no conflict of interest.

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References

[1] Fink C, Zapp M, Benedetto KP, Hackl W, Hoser C, Rieger M. Tibial tunnel enlargement following anterior cruciate ligament reconstruction with patellar tendon autograft. Arthroscopy 2001;17:138–43.
[2] Fauno P, Kaalund S. Tunnel widening after hamstring anterior cruciate ligament reconstruction is influenced by the type of graft fixation used: a prospective randomized study. Arthroscopy 2005;21:1337–41.
[3] Hwang DH, Shetty GM, Kim JI, Kwon JH, Song JK, Munoz M, et al. Does press-fit technique reduce tunnel volume enlargement after anterior cruciate ligament reconstruction with autologous hamstring tendons? A prospective randomized computed tomography study. Arthroscopy 2013;29:83–8.
[4] Sabat D, Kundu K, Arora S, Kumar V. Tunnel widening after anterior cruciate ligament reconstruction: a prospective randomized computed tomography-based study comparing 2 different femoral fixation methods for hamstring graft. Arthroscopy 2011;27:776–83.
[5] Webster KE, Feller JA, Hameister KA. Bone tunnel enlargement following anterior cruciate ligament reconstruction: a randomised comparison of hamstring and patellar tendon grafts with 2-year follow-up. Knee Surg Sports Traumatol Arthrosc 2001;9:86–91.
[6] Wilson TC, Kantaras A, Atay A, Johnson DL. Tunnel enlargement after anterior cruciate ligament surgery. Am J Sports Med 2004;32:543–9.
[7] Kawaguchi Y, Kondo E, Kitamura N, Kai S, Inoue M, Yasuda K. Comparisons of femoral tunnel enlargement in 169 patients between single-bundle and anatomic double-bundle anterior cruciate ligament reconstructions with hamstring tendon grafts. Knee Surg Sports Traumatol Arthrosc 2011;19:1249–57.
[8] Xu Y, Ao Y, Wang J, Yu J, Cui G. Relation of tunnel enlargement and tunnel placement after single-bundle anterior cruciate ligament reconstruction. Arthroscopy 2011;27:923–32.
[9] Orrego M, Larrain C, Rosales J, Valenzuela L, Matas J, Durruty J, et al. Effects of platelet concentrate and a bone plug on the healing of hamstring tendons in a bone tunnel. Arthroscopy 2008;24:1373–80.
[10] Hoher J, Moller HD, Fu FH. Bone tunnel enlargement after anterior cruciate ligament reconstruction: fact or fiction? Knee Surg Sports Traumatol Arthrosc 1998;6:231–40.
[11] Rodeo SA, Kawamura S, Kim H-J, Dynybil C, Ying L. Tendon healing in a bone tunnel differs at the tunnel entrance versus the tunnel exit: an effect of graft–tunnel motion? Am J Sports Med 2006;34:1790–800.
[12] Tsuda E, Fukuda Y, Loh JC, Debski RE, Fu FH, Woo SL. The effect of soft-tissue graft fixation in anterior cruciate ligament reconstruction on graft–tunnel motion under anterior tibial loading. Arthroscopy 2002;18:960–7.
[13] Buelow JU, Siebold R, Ellermann A. A prospective evaluation of tunnel enlargement in anterior cruciate ligament reconstruction with hamstrings: extracortical versus anatomical fixation. Knee Surg Sports Traumatol Arthrosc 2002;10:80–5.
[14] Järvelä T, Moisala A-S, Paakkala T, Paakkala A. Tunnel enlargement after double-bundle anterior cruciate ligament reconstruction: a prospective, randomized study. Arthroscopy 2008;24:1349–57.
[15] Lubowitz JH, Ahmad CS, Anderson K. All-inside anterior cruciate ligament graft-link technique: second-generation, no-incision anterior cruciate ligament reconstruction. Arthroscopy 2011;27:717–27.
[16] Mayr R, Heinrichs CH, Eichinger M, Coppola C, Schmoelz W, Attal R. Biomechanical comparison of 2 anterior cruciate ligament graft preparation techniques for tibial fixation: adjustable-length loop cortical button or interference screw. Am J Sports Med 2015;43:1380–5.
[17] Marchant MH, Willimon SC, Vinson E, Pietrobon R, Garrett WE, Higgins LD. Comparison of plain radiography, computed tomography, and magnetic resonance imaging in the evaluation of bone tunnel widening after anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc 2010;18:1059–64.
[18] Araki D, Kuroda R, Matsumoto T, Nagamune K, Matsushita T, Hoshino Y, et al. Three-dimensional analysis of bone tunnel changes after anatomic double-bundle anterior cruciate ligament reconstruction using multidetector-row computed tomography. Am J Sports Med 2014;42:2234–41.
[19] Greenhouse SW, Geisser S. On methods in the analysis of profile data. Psychometrika 1959;24:95–112.
[20] Landis JR, Koch GG. The measurement of observer agreement for categorical data. Biometrics 1977;33:159–74.
[21] Moisala AS, Jarvela T, Paakkala A, Paakkala T, Kannus P, Jarvinen M. Comparison of the bioabsorbable and metal screw fixation after ACL reconstruction with a hamstring autograft in MRI and clinical outcome: a prospective randomized study. Knee Surg Sports Traumatol Arthrosc 2008;16:1080–6.
[22] Fahey M, Indelicato PA. Bone tunnel enlargement after anterior cruciate ligament replacement. Am J Sports Med 1994;22:410–4.
[23] Myers P, Logan M, Stokes A, Boyd K, Watts M. Bioabsorbable versus titanium interference screws with hamstring autograft in anterior cruciate ligament reconstruction: a prospective randomized trial with 2-year follow-up. Arthroscopy 2008;24:817–23.
[24] Stener S, Ejerhed L, Sernert N, Laxdal G, Rostgard-Christensen L, Kartus J. A long-term, prospective, randomized study comparing biodegradable and metal interference screws in anterior cruciate ligament reconstruction surgery: radiographic results and clinical outcome. Am J Sports Med 2010;38:1598–605.
[25] Ntagiopoulos PG, Demey G, Tavernier T, Dejour D. Comparison of resorption and remodeling of bioabsorbable interference screws in anterior cruciate ligament reconstruction. Int Orthop 2015;39:697–706.
[26] Greis PE, Burks RT, Bachus K, Luker MG. The influence of tendon length and fit on the strength of a tendon-bone tunnel complex. A biomechanical and histologic study in the dog. Am J Sports Med 2001;29:493–7.
[27] Mayr R, Heinrichs CH, Eichinger M, Smekal V, Schmoelz W, Attal R. Preparation techniques for all-inside ACL cortical button grafts: a biomechanical study. Knee Surg Sports Traumatol Arthrosc 2016;24:2983–9.
[28] Harris NL, Indelicato PA, Bloomberg MS, Meister K, Wheeler DL. Radiographic and histologic analysis of the tibial tunnel after allograft anterior cruciate ligament reconstruction in goats. Am J Sports Med 2002;30:368–73.