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In Vivo Analysis of Dynamic Graft Bending Angle in Anterior Cruciate Ligament Reconstructed Knees during Downward Running and Level Walking: Comparison of Flexible and Rigid Drills for Trans-Portal Technique

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Abstract

Purpose—To determine *in vivo* dynamic graft bending angle (GBA) in anterior cruciate ligament (ACL) reconstructed knees, correlate the angle to tunnel positions and tunnel widening, and evaluate the effects of two femoral tunnel drilling techniques on GBA.

Methods—Patients with an isolated ACL injury undergoing reconstruction were included from 2011 to 2012. Trans-portal techniques were used to create femoral tunnels. Tunnel locations were determined using 3D-CT. Tibio-femoral kinematics during treadmill walking and running were assessed using dynamic stereo X-ray analysis 6 months and 2 years postoperatively. The GBA was calculated from the 3D angle between the graft and femoral tunnel vectors at each motion frame. Cross-sectional area of femoral tunnels were measured at 6 months and compared to initial size to assess tunnel widening.

Results—A total of 54 patients were included. Use of flexible drills resulted in significantly higher GBA during walking ($80.6^\circ \pm 7.8^\circ$; $p < 0.001$) and running ($80.5^\circ \pm 9.0^\circ$; $p = 0.025$) than rigid drills (walking: $67.5^\circ \pm 9.3^\circ$, running: $74.1^\circ \pm 9.6^\circ$). It led to greater tunnel widening of $113.9 \pm 17.6\%$, compared with rigid drills of $97.7 \pm 17.5\%$ ($p = 0.003$). Femoral and tibial apertures were located in similar anatomic positions in both groups, but femoral tunnel exits were located more anteriorly ($p < 0.001$) in the flexible drill group. Higher GBA was highly correlated with

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Disclosure of Potential Conflicts of Interest

The authors declare that they have no conflict of interest.

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anterior location of femoral exits ($r=0.63$, $p<0.001$) and moderately correlated with greater tunnel widening ($r=0.48$, $p<0.001$).

Conclusions—High GBA was identified during dynamic activities after anatomic ACL reconstruction using a trans-portal femoral tunnel drilling technique. The GBA was greater when flexible drills were used. The high bending angle resulted from more anterior location of femoral tunnel exits, and correlated with early bone tunnel widening at 6 months. These results suggest that high GBA may increase stress on the bone-graft interface and contribute to greater tunnel widening after anatomic ACL reconstruction, although clinical impact should be further investigated.

Level of Evidence—Level III, retrospective comparative study

Introduction

Techniques for anterior cruciate ligament (ACL) reconstruction have focused more recently on anatomic placement of bone tunnels (within the native insertion site), in order to better restore normal knee kinematics and improve clinical outcomes¹⁻⁷. The trans-portal technique enables placement of femoral tunnels independently from tibial tunnels, and is generally more effective for locating femoral tunnels anatomically than the traditional trans-tibial technique⁸⁻¹². The trans-portal technique, however, has been associated with risks including short femoral tunnel length, narrow arthroscopic view in hyper knee flexion, articular cartilage damage and posterior wall blow-out¹³⁻¹⁶. In order to decrease these risks, a flexible guidewire and drill system has been introduced^{17,18}. This technique provides improved visualization of the ACL femoral footprint without hyper knee flexion, more reliable placement of femoral tunnels within anatomic insertion site, longer femoral tunnel length and reduced chondral damage^{19,20}.

Despite the reported advantages of anatomic ACL reconstruction, some concerns remain regarding the techniques used. Partial damage or poor synovial coverage of the reconstructed graft have been reported during second-look arthroscopy, and may be related to increased laxity²¹⁻²⁴. A recent analysis based on the Danish ACL registry reported an increased revision rate with anatomic ACL reconstruction, compared with the conventional trans-tibial technique²⁵. It has been suggested that anatomic reconstruction may contribute to graft damage or poor graft healing by creating higher stress between the bone and the graft, due to impingement against intercondylar wall^{26,27}, higher forces or tension applied in the reconstructed graft near extension^{2,28,29}, greater length change of the graft³⁰ and steeper graft bending angles at the tunnel aperture³¹⁻³³. Simple physics would suggest that a properly sized, anatomically placed graft should not “impinge” any more than the native ACL, and should undergo similar stress and length change³⁴⁻³⁸. However, the issue of steep graft bending angle is a specific phenomenon seen only in the reconstructed graft, but not in the native ACL, because the graft-tunnel construct cannot recreate the native insertion site anatomy at its tunnel aperture. If the graft changes direction at the femoral tunnel aperture, redirecting forces or abrasive forces may be created and they could cause a localized area of increased graft stress at the sharp aperture edge, potentially contributing to graft damage, widening of the bone tunnel aperture³⁹⁻⁴³, and/or increased knee laxity over time.

The graft bending angle (GBA) is defined as the angle between the bone tunnel and the line connecting the femoral and tibial tunnel apertures. The repetitive bending or the abrasive force at the sharp femoral tunnel aperture may cause excessive stress on the graft, which can be a possible cause of graft damage or poor healing after ACL reconstruction^{40,44,45}. Graft deformation at the femoral aperture corner has been reported after anatomic ACL reconstruction when applying cyclic load to cadavers⁴⁶. Since GBA is affected by intra-articular tunnel apertures and extra-articular tunnel exits, different tunnel locations and orientations created by two kinds of femoral drills can lead to varying GBA. GBA is also influenced by the position of the tibia relative to the femur, which is task-dependent. Therefore, *in vivo* dynamic, weight bearing activities can provide a better indication of the GBA likely to affect the graft than static tests⁴⁷⁻⁵⁰. Because downhill running is more stressful on ACL than level-ground walking or running⁵¹, more steep graft bending and higher graft-bone forces could occur.

The purpose of this study was to determine *in vivo* dynamic graft bending angle (GBA) in ACL reconstructed knees, correlate the angle to tunnel positions and tunnel widening, and evaluate the effects of two femoral tunnel drilling techniques on GBA. We hypothesized that: 1) steep graft bending could occur during dynamic knee motion; 2) drilling technique will affect the GBA; and 3) higher GBA would be associated with increased bone tunnel widening.

Materials and Methods

From March 2011 to December 2012, potential subjects were identified through their enrollment in a clinical trial on anatomic anterior cruciate ligament (ACL) reconstruction⁵². Inclusion criteria were an isolated ACL injury, range of age (14 to 50 years), activity level (participation in level 1 or 2 activities for at least 100 hours per year), tibial insertion site size from 14 to 18 mm and quadriceps tendon thickness over 7 mm in clinical MRI, and closed physes based on clinical radiographs. Exclusion criteria were patients with previous history of ACL reconstruction, meniscal or any other knee surgery. Concomitant ligament injuries greater than grade I under anesthesia and chondral lesions with grade 3 or 4 Outerbridge classification were also excluded. The specific indication for surgery was ACL deficiency with a symptom of knee instability. Rigid drills were used in 2011, then consecutively, flexible drills were used in 2012 in order to create the femoral tunnels. A high-resolution computed tomography (CT) scan was performed with $0.31 \times 0.31 \times 0.6$ mm voxels 6 months after surgery. Dynamic knee motion was assessed using dynamic stereo x-ray analysis (DSX) system 6 months and 2 years after surgery. All subjects gave their informed consent before they were included and a retrospective data analysis for the study was approved by the appropriate institutional review board (IRB) for human subject research.

Surgical procedure

The basic concept of anatomic ACL reconstruction and its procedures were recently reported in detail⁵³⁻⁵⁵. The surgical procedure is briefly described here. The affected knee was held in 90° of flexion using an arthroscopic leg holder. A 10-mm quadriceps tendon autograft with a

bone plug was harvested. Three arthroscopic portals were established. The anterolateral portal was positioned as high as the inferior pole of the patella, which gave an excellent arthroscopic view over the tibial footprint of the ACL. The anteromedial portal was used to allow optimal visualization of the lateral wall of the intercondylar notch, including the femoral ACL insertion site. The accessory medial portal (AMP) was established far medially, just above the anterior horn of the medial meniscus, in a position allowing direct access to the center of the ACL femoral insertion site while avoiding damage to articular cartilage during femoral drilling. A guide wire was introduced through the AMP portal and placed at the center of femoral insertion site. In 20 cases, the femoral tunnel was drilled using a 2.4-mm straight guide pin and rigid drills, with the knee kept in maximal flexion (Rigid drill group). Then a dilator was used to make the tunnel to the desired diameter (10.5 ± 0.4 mm). In the consecutive 34 cases, a flexible guide wire (VersiTomic® Flexible Reaming System; Stryker, Mahwah, NJ) and drills were used with the knee positioned in 100 to 110° flexion (Flexible drill group). The dilator was used finally in the same way (diameter: 10.3 ± 0.5 mm). The tibial tunnel was also created within the native ACL footprint, and independently from the femoral tunnel. In all cases, quadriceps tendon autografts were used, with the bone block fixed to the femoral side using extracortical fixation (EndoButton CL BTB, Smith & Nephew Endoscopy). Tibial fixation was performed using interference screws (Biosure Sync, Smith & Nephew Endoscopy).

Assessment of Dynamic knee motion

In order to assess *in vivo* dynamic GBA changes, dynamic knee motion was examined during level walking and downhill running on an instrumented treadmill. While walking is the most common physical activity, downhill running was also selected because it is relatively stressful on the ACL⁵¹ but can be performed in a controlled, repeatable fashion within the laboratory environment and is unlikely to put the individual at significant risk for re-injury. Walking was performed at 1.3 m/s. Downhill running was performed at 2.5 m/s with a 10° slope (**Fig. 1a**). Kinematics data were collected from shortly before footstrike through midstance/late stance. Gait cycle timing was determined using the vertical ground reaction force from the instrumented treadmill. Three trials were collected and averaged for each subject and activity.

Six degrees of freedom tibio-femoral kinematics, including anterior tibial translation and tibial rotation, were determined using dynamic stereo x-ray analysis (DSX) 6 months and 2 years postoperatively, as previously described^{56,57} (**Fig. 1b**). The DSX system consists of 2 gantries containing a pulsed x-ray source and detectors with an interbeam angle of 60° and enough space to perform treadmill walking and running (1.8 m source to detector distance). This system is capable of tracking knee kinematics with validated dynamic precision in the order of ± 0.5 mm or better⁵⁶. Biplane radiographic images were acquired during walking at 100 frames/s, with 90 kVp, 125 mA, 1 ms duration pulsed exposures. Running data were acquired at 150 frames/s, with the same radiographic protocol.

Measurement of Graft bending angle (GBA)

The locations of the femoral and tibial tunnel aperture centers and the proximal femoral tunnel exits were identified from 3D bone models generated from the high-resolution CT,

using commercially available medical imaging software (Mimics®, Materialise, Leuven, Belgium). GBA was calculated from the 3D angle between the intra-articular graft and tunnel using the formula below (as reported by previous studies^{32,33}), with $\mathbf{v}^{FTA \rightarrow FTE}$ defined as the vector from the femoral tunnel aperture to the femoral tunnel exit (tunnel vector), and $\mathbf{v}^{TTA \rightarrow FTA}$ defined as the vector from the tibial tunnel aperture to the femoral tunnel aperture (graft vector):

$$GBA = \cos^{-1} \frac{\mathbf{v}^{FTA \rightarrow FTE} \cdot \mathbf{v}^{TTA \rightarrow FTA}}{|\mathbf{v}^{FTA \rightarrow FTE}| |\mathbf{v}^{TTA \rightarrow FTA}|}$$

In order to analyze GBA during dynamic knee movement, the two vectors were determined at each motion frame from the dynamic positions of the three CT-identified landmarks. In other words, bones were tracked from biplane x-ray and relative positions of those three landmarks were determined during gait cycles. Thus, *in vivo* dynamic GBA was measured in 3D, within the plane defined by the three identified points (**Fig. 2**).

Evaluation of Bone tunnel widening

Cross-sectional areas of femoral bone tunnels were assessed to evaluate bone tunnel widening as a proxy for local stress between the bone and the graft at the femoral tunnel aperture⁴³. First, bone tunnel walls were segmented from the CT slice data to create surface models. CT is more reliable than MRI or X-ray for evaluating bone tunnel widening⁵⁸, and it was already available as it is required for the DSX model-based tracking method. Next, a cylinder was fit to the tunnel to define the longitudinal axis. The surface model of the bone tunnel was sliced with parallel cuts perpendicular to the long axis of the tunnel and the cross-sectional area just beneath the aperture was measured using 3D imaging software (**Fig. 3a,b**). The percentage of tunnel widening was determined by dividing the aperture area by the nominal tunnel size, determined from the diameter of the tunnel dilator used, as previously described^{59,60}.

Data Analysis

GBA (mean and maximum values during stance) and bone tunnel widening were compared between flexible and rigid drill groups using Student's *t*-test. Locations of the tunnel aperture centers and the femoral tunnel exits were determined in three directions (proximal-distal, anterior-posterior and medial-lateral, with the coordinate origin set at the lateral femoral condyle), normalized to femoral size and compared between the two drill groups using Student's *t*-test. The relationship between average or maximum values of GBA and femoral tunnel exit locations were assessed using Pearson's correlations. Correlations between GBA and bone tunnel widening, or each kinematic parameters of anterior tibial translation and tibial rotation (values in affected knees and side-to-side difference) were assessed similarly. Paired *t*-tests were used to analyze differences of mean GBA during walking and running from 0 to 15% of the gait cycle after footstrike. The StatView 5.0 software program (SAS Institute Inc., Cary, NC) was used for the statistical analysis, with significance level of $p < 0.05$.

Results

A total of 54 potential subjects (37 male/17 female) with a mean age of 21 years were identified for inclusion in the study. Five subjects were excluded: 2 could not complete the dynamic activities on the treadmill; 2 did not stay within the DSX field of view, and one was lost to follow-up at 6 months. At 6 months, GBA and kinematics data from DSX was obtained in 49 subjects (90.7%; 32 male/17 female), with 18 rigid drill cases and 31 flexible drill cases. At 2 years, kinematics data were obtained from 46 patients (85.2%; 30 male/16 female), with 16 rigid drill cases and 30 flexible drill cases, because 2 subjects were lost to follow-up and 1 injured his contra-lateral ACL.

The mean ($\pm$ S.D.) graft bending angle (GBA) at footstrike was $71.9 \pm 12.3^\circ$ during walking and $73.6 \pm 12.3^\circ$ during running. It significantly increased to $78.1 \pm 9.8^\circ$ for walking ($p < 0.001$) and $81.5 \pm 11.1^\circ$ for running through mid-stance ($p < 0.001$) (**Fig. 4**). The mean GBA was significantly higher during running than walking (mean difference from footstrike through mid-stance: 3.1° ; $p < 0.001$).

Compared with the rigid drill group, the flexible drill group demonstrated substantially higher average and maximum GBA for both walking ($p < 0.001$) and running ($p = 0.025$ for mean and $p = 0.031$ for maximum GBA, respectively), as well as greater tunnel widening ($p = 0.003$) (**Table 1**).

Tunnel locations of all cases are presented in **Fig. 5a,b**. Femoral and tibial apertures were located similarly in both rigid and flexible drill groups ($p = 0.657$ for anterior-posterior and $p = 0.824$ for proximal-distal, respectively). Femoral tunnel exits were located more anteriorly ($p < 0.001$) and laterally ($p < 0.001$) in the flexible drill group compared to the rigid drill group (**Fig. 5a,b**). More anterior location of femoral tunnel exits were well correlated with higher GBA during walking ($r = 0.63$ for mean and 0.61 for maximum values, both $p < 0.001$) and running ($r = 0.45$, $p = 0.001$ for mean and $r = 0.40$, $p = 0.004$ for maximum values) (**Fig. 5c,d**, **Table 2**). Tunnel widening was moderately correlated with GBA for both walking ($r = 0.48$ for mean and $r = 0.49$ for maximum, both $p < 0.001$) and running ($r = 0.37$, $p = 0.008$ for mean and $r = 0.34$, $p = 0.019$ for maximum) (**Table 2**).

Side-to-side difference of anterior tibial translation (ATT) was 1.1 ± 2.5 mm during walking and 0.9 ± 2.2 mm during running at 2 years. Side-to-side difference of tibial rotation was $0.6 \pm 4.1^\circ$ (external) during walking and $1.7 \pm 3.5^\circ$ (external) during running at 2 years. There was no significant difference in kinematic parameters between the rigid and the flexible drill groups ($p = 0.878$ for ATT and $p = 0.743$ for tibial rotation during walking, and $p = 0.505$ for ATT and $p = 0.202$ for tibial rotation during running). No clear relationship was found between GBA and each kinematics parameter of ATT or tibial rotation at 6 months and 2 years.

Discussion

The most important findings of this study were that a steep GBA was identified at footstrike during dynamic activities after ACL reconstruction, especially with flexible drills. While femoral and tibial tunnel apertures were located similarly in both drilling groups, femoral

exits in the flexible drill group were positioned significantly more anteriorly, leading to higher bending angles of the graft at the femoral aperture and larger bone tunnel widening at 6 months after surgery, thus our hypotheses were affirmed. The significant correlation between higher GBA and early tunnel widening may suggest increased stress between the bone and the graft at the femoral tunnel aperture.

We assessed the dynamic knee motion from footstrike to mid-stance. During this phase, in addition to the stress to the joint due to the impact on the ground^{61,62}, the ACL is subjected to relatively higher tension with the knee at near full extension to mild flexion^{36,63}. The ACL-reconstructed knees in our study were also near full extension at footstrike, and this means the graft was subjected to higher tension during the phase. The combination of steep GBA and high graft tension may have increased the interference between the bone and the reconstructed graft. Previous studies have also reported steep GBA of about 70° after ACL reconstruction using trans-portal technique with rigid drills^{31,33,39-41}. Although these studies assessed GBA statically with knees in a fixed position, their postoperative CT examinations were performed at near extension, thus they led to similarly high GBA. A comparison study of trans-portal and trans-tibial ACL reconstruction reported that antero-medial and postero-lateral graft bending angles with trans-portal technique were significantly more acute (steep) than with single-bundle trans-tibial technique³³. Recent studies comparing GBA between trans-portal and outside-in ACL reconstruction by postoperative CT have reported that outside-in technique resulted in even steeper graft bending than in trans-portal technique, with about 80° GBA^{31,40,41}.

Significantly steeper GBA was observed in the flexible drill group in our study. Of the three landmarks used to determine the GBA, only the femoral tunnel exits were different between the groups (with the flexible drill exit points positioned substantially more anteriorly). The significant correlation between anterior location of femoral exits and increased GBA support the conclusion that the more anterior exit points resulting from use of the flexible drill are the primary cause of the increased GBA. These results are consistent with a previous study that reported higher GBA and more anterior location of femoral exits with an outside-in drilling technique, compared to lower GBA with trans-portal drilling (which resulted in femoral exits at approximately the level of the lateral epicondyle)⁴⁰. A study using computer simulation also concluded that more proximal location of femoral exits could reduce graft bending angles without changing the anatomic femoral and tibial aperture position⁶⁴. Another previous study, however, reported apparently contradictory results, with lower GBA with flexible (as opposed to rigid) drills³⁹. A different flexible drill system was used (Clancy Anatomic Cruciate Guide System; Smith & Nephew), suggesting that the effect of flexible vs. rigid drilling may be dependent on the type of flexible drill system used (as well as the specific surgical technique).

In this study, we analyzed *in vivo* GBA in ACL-reconstructed knees during dynamic weight bearing activities and to relate GBA to tunnel enlargement. Most of the previous studies on GBA assessed the knee at only one static phase by CT^{31,33,40-42}. A previous cadaver study demonstrated that GBA changes significantly with knee motion³², and this effect may be even larger when the knee is under dynamic, high-magnitude loads that alter knee kinematics. Our results showed significantly larger bone tunnel widening in the flexible drill

group than in the rigid drill group. Moderate correlation between the tunnel widening and both of average and maximum values of GBA during level walking suggests that high GBA by the flexible drills may contribute to larger tunnel widening. A previous study also showed an association between more anterior or distal location of femoral exits and greater tunnel enlargement⁴⁵, consistent with our study.

Given concerns about the possible effects of tunnel widening on graft-tunnel healing (as well as the potential problems caused by excess tunnel enlargement should a revision procedure be required), the findings of this study are clinically significant. Our finding that steeper GBA is associated with greater bone tunnel widening suggests that the resulting higher graft-bone forces at the femoral aperture at footstrike may have detrimental effects for early graft-tunnel healing, although kinematics data at 2 years showed good stability with small variances and no clear correlation with GBA. These results further suggest that the use of flexible drills may increase GBA and bone tunnel widening. The linear regression line of Tunnel widening (%) = $0.9 \times \text{mean GBA} + 41$ (**Table 2.**) means that if mean GBA during walking is 11° higher, tunnel widening may increase almost 10%, although further evidence are needed to discuss the influence of GBA on graft-tunnel healing. A quadriceps tendon autografts with a bone block was used in this study, but a use of soft-tissue grafts may lead to delayed graft-tunnel healing and increased tunnel widening, as previous studies reported^{59,60,65}. Thus, it may be worthwhile to consider alternative designs and uses of flexible drills to create tunnel exits that do not increase GBA.

Limitations

One of the limitations of this study is that it is a secondary analysis of data collected for a clinical trial⁵², and the use of drill type was not randomized. However, the femoral size at the baseline was similar between the two groups, and there were no other differences identified between the groups that would be likely to affect the results. Secondly, the range of motion examined in the dynamic activity was limited and knee flexion over 90° was not examined. Previous studies on GBA during knee motion have shown lower bending angle of reconstructed grafts in over 90° knee flexion than in 0° to 30° flexion^{32,64}, therefore assessment of motion at these lower flexion angles should be clinically relevant. Thirdly, we didn't have a trans-tibial control group, which might have lower GBA at 0° knee flexion^{33,64}. However, in clinical practice, we didn't use the trans-tibial technique during this period because it could sometimes lead to non-anatomical tunnel positions⁸⁻¹². Tunnel widening was assessed only at 6 months and no CT examination was performed at 24 months, but tunnel widening mainly develops during the first months after surgery^{43,66}, and we focused on graft-tunnel healing in the early postoperative period.

Conclusion

High graft bending angles were identified during dynamic activities after anatomic ACL-reconstruction using a trans-portal femoral tunnel drilling technique. The GBA was greater when flexible drills were used. The high bending angle resulted from more anterior location of femoral tunnel exits, and correlated with early bone tunnel widening at 6 months. These results suggest that high GBA may increase stress on the bone-graft interface and contribute

to greater tunnel widening after anatomic ACL reconstruction, although clinical impact should be further investigated.

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Fig. 1.

(a) A subject running downhill on a treadmill in the high-speed dynamic stereo X-ray system. Images are acquired simultaneously at 150 frames/sec for the 2 views (60° separation). (b) CT-based 3D bone model was matched to the biplane X-ray image and tibio-femoral kinematics were determined.

Fig. 2. Graft bending angle at the femoral tunnel aperture was measured in 3D on a plane fit to the three points of femoral exit, femoral and tibial aperture centers.

Fig. 3.
(a) The bone tunnel in 3D-CT was cut perpendicular to the long axis of the tunnel. (b) The cross sectional area beneath the aperture was measured digitally.

Fig. 4.

Graft bending and knee flexion angle changes during level walking and downhill running are shown. The mean graft bending angle during running was significantly higher ($p < 0.001$) than that during walking in the first 15 % of gait cycle.

GBA during Walking

GBA during Running

Fig. 5.

(a). Tunnel locations of flexible (blue) and rigid (red) drill groups were identified in AP view. The trans-epicondylar axis was set as the horizontal axis. Femoral exits in flexible drill groups were located slightly lateral to those for the rigid drill groups ($p < 0.001$). (b) Tunnel locations in lateral view is shown. The lateral epicondyle was set as the coordinate origin. Femoral exits by flexible drills (blue) were located significantly anterior ($p < 0.001$) than those by rigid drills. (c) Color map of graft bending angle (GBA) average during level walking is shown according to its bending steepness. Anterior locations of exits were well correlated with high GBA ($R = 0.63$, $p < 0.001$). (d) Color map of GBA average during downhill running is shown. It was also correlated with anterior location of exits ($R = 0.45$, $p = 0.001$) and significantly higher than the angles during walking ($p < 0.001$).

Table 1

Graft bending angles (GBA) and bone tunnel widening

	Flexible (N=31)	Rigid (N=18)	Significance
Level walking			
Mean GBA	80.6° ± 7.8°	67.5° ± 9.3°	P < 0.001
Maximum GBA	84.8° ± 8.1°	71.6° ± 9.6°	P < 0.001
Downward running			
Mean GBA	80.5° ± 9.0°	74.1° ± 9.6°	P = 0.025
Maximum GBA	86.8° ± 9.4°	80.3° ± 10.6°	P = 0.031
Tunnel widening (0 to 6 months)	113.9 % ± 17.6 %	97.7 % ± 17.5 %	P = 0.003

Mean ± S.D. are presented.

GBA = graft bending angle.

Flexible = flexible drill group, Rigid = rigid drill group.

Table 2

Correlation between graft bending angles and locations of femoral exit, or bone tunnel widening

Level Walking (N=49)		Locations of Femoral exit			Tunnel Widening (TW)
		Proximal/Distal	Anterior/Posterior	Lateral/Medial	
Mean GBA	Corr (R) Significance	-0.21 p = 0.160	0.63 p < 0.001	0.51 p < 0.001	0.48 p < 0.001 TW(%)=0.9GBA+41
Maximum GBA	Corr (R) Significance	-0.22 p = 0.142	0.61 p < 0.001	0.48 p < 0.001	0.49 p < 0.001 TW(%)=0.9GBA+38
Downward Running (N=49)					
Mean GBA	Corr (R) Significance	-0.05 p = 0.741	0.45 p = 0.001	0.27 p = 0.069	0.37 p = 0.008 TW(%)=0.7GBA+50
Maximum GBA	Corr (R) Significance	-0.05 p = 0.748	0.40 p = 0.004	0.19 p = 0.189	0.34 p = 0.019 TW(%)=0.6GBA+55

Locations of femoral exit were based on coordinates and degrees with the origin located at the epicondyle.

GBA = graft bending angle.