Original Article

In vivo gait kinematics of the knee after anatomical and non-anatomical single-bundle anterior cruciate ligament reconstruction—a prospective study

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Background: The factors that influence functions of knees after anterior cruciate ligament reconstruction (ACLR) still remains uncertain. The functional restoration of knees after ACLR can be reflected on gait kinematics restoration. The purpose of this study was to evaluate the gait kinematics and clinical outcomes of knees after anatomical and non-anatomical single-bundle ACLR during level walking.

Methods: Thirty-four patients with unilateral primary single-bundle ACLR and 18 healthy people were recruited. Patients were divided into anatomical reconstruction group (AR group; n=13) and non-anatomical reconstruction group (Non-AR group; n=21) according to Bernard Quadrant method. The ACL graft orientations on coronal and sagittal planes were measured on 3D models from medical images. The 6 degrees of freedom (DOF) kinematics of knees and range of motion (ROM) of 6 DOF kinematics were measured with a portable optical tracking system. The comparison of 6 DOF kinematics and ROM of 6 DOF kinematics were performed between the ACLR knees and contralateral knees. The following assessments were also performed including clinical examination, KT-2000 arthrometer measurement, International Knee Documentation Committee (IKDC) and Lysholm scores.

Results: All patients reached a minimum follow-up of 6 months (10±4 months). For AR group and Non-AR group, no statistically significant differences were observed in gait kinematics between the ACLR knees and contralateral knees. No statistically significant differences between the ACLR knees and contralateral knees were observed in terms of ROM of 6 DOF kinematics in AR group. However, in Non-AR group, the ACLR knees exhibited significant ROM of anterior-posterior translation by approximately 0.5 cm than contralateral knees (P=0.0080). No statistically significant differences between the two groups were observed regarding IKDC subjective score, Lysholm score and KT-2000 arthrometer test.

Conclusions: The anatomical ACLR can restore close to normal gait kinematics and ROM of 6 DOF kinematics compared with non-anatomical ACLR. The ACL graft after anatomical ACLR simulated native ACL fibers to function in terms of graft orientation.

Keywords: Anatomical anterior cruciate ligament reconstruction (ACLR); non-anatomical reconstruction (non-AR); single-bundle; anterior cruciate ligament graft orientation; knee kinematics

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Introduction

Anterior cruciate ligament (ACL) maintains knee stability not only by controlling anterior translation of the tibia but also restricting knee rotation in the axial and transverse plane (1). The increased anterior translation of tibia and knee rotational imbalance accompanies ACL injuries (2). Moreover, ACL injuries alter the kinematics of knees with or without meniscal tears during level walking test (3). After ACL tears, the knee joint remains unstable and more prone to further injuries like the damage to menisci and articular cartilage which may lead to premature arthritis (4,5). Many studies have reported that anatomical reconstruction (AR) can restore superior rotational stability and clinical outcomes than non-anatomical reconstruction (non-AR) (6-11). However, few studies have been reported on the reasons for this discrepancy.

Gait kinematics, the most common daily activity, are closely related to knee functions and stability. The abnormal knee kinematics often accompanies ACL injuries (12-14). Zhang *et al.* (3) showed that the ACL deficient knees, with or without meniscal tears, exhibited significant less flexion and more femoral external rotation than ACL intact knees. The abnormal gait kinematics was found to be a risk factor for lower limb tendinopathy (15). Moreover, abnormal kinematics may be one of the possible reasons for subsequent joint degenerations after anterior cruciate ligament reconstruction (ACLR) (16,17). Imhauser *et al.* (16) performed a cadaveric study to simulate clinical tests of anterior and rotational stability after ACLR. They concluded that abnormal contact stress was associated with altered kinematics after ACLR, which may affect the progression of osteoarthritis. Andriacchi and Favre (17) summarized the *in vivo* mechanical signals influenced cartilage health and progression to knee osteoarthritis. So, kinematics analysis should be an important index to evaluate functional restoration of knees after ACLR.

Graft orientation caused by the placement of tunnel aperture has been reported to affect the knee functions and clinical outcomes (18-22). Musahl *et al.* (19) performed a cadaveric study with the cadaveric knees tested in response to a 134-N anterior load and a combined 10-N.m valgus and 5-N.m internal rotation load. They concluded a femoral tunnel position inside the anatomical footprint resulted in knee kinematics closer to the intact knee. Zantop *et al.* (22) also summarized anatomical tunnel placement of anteromedial (AM) and posterolateral bundles can restore intact knee kinematics based on a cadaveric study with the knees in response to a 134-N anterior tibial load and a combined rotatory load of 10 N.m valgus and 4 N.m internal tibial rotation using a robotic/universal force moment sensor testing system. Howell *et al.* (18,21) measured the MR signal intensity of unimpinged and impinged ACL grafts. They found impinged ACL grafts showed an increase in signal intensity in the distal two-thirds of the graft. While the unimpinged grafts with more vertical graft orientation on the coronal plane remained low signal intensity. Brophy *et al.* (20) reported that more vertical graft orientation may be a reason for ACL revision. These studies demonstrated that the ACL graft orientation may be a determinant for the function restoration after ACLR. However, the effect of graft orientations on *in vivo* gait kinematics has rarely been reported.

To the best of our knowledge, few studies have been performed to compare gait kinematics between ACLR knees and contralateral normal knees after anatomical and non-anatomical single-bundle ACLR, separately. The purpose of this study was to evaluate the gait kinematics and clinical outcomes of knees after anatomical and non-anatomical single-bundle ACLR during level walking. A portable optical tracking system was used to measure the 6 degrees of freedom (DOF) kinematics of the single-bundle ACLR knees, the ACL-intact (ACLI) contralateral normal knees and the knees of normal people during treadmill gait. This study was expected to provide references for the placement of tunnel aperture and graft orientation during ACLR.

Methods

Study design

After approval from the Institutional Review Board of Nanjing Drum Tower Hospital (2019-024-01) and obtaining informed consent, 34 patients (28 males, 6 females; age range, 18–46 years; BMI range, 19.3–37.7 kg/m^2) were recruited. The inclusion criteria included unilateral primary single-bundle ACLR, closed epiphyseal plate and

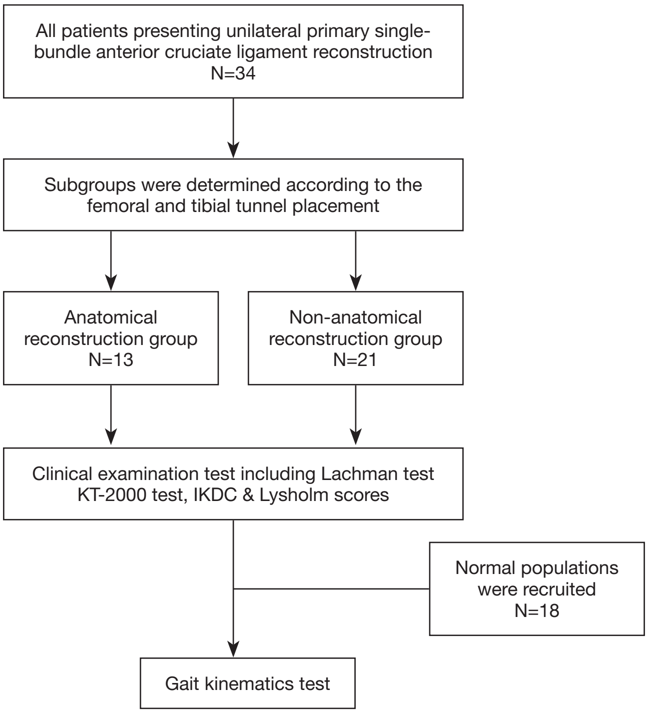

Figure 1 Study design flow diagram.

healthy volunteers. The exclusion criteria included multi-ligament injuries, lower extremity or spine deformities, positive anterior draw test or Lachman test. Subgroups were determined according to the femoral and tibial tunnel placement, including anatomical reconstruction group (AR group) and non-anatomical reconstruction group (Non-AR group). The International Knee Documentation Committee (IKDC) evaluation form and Lysholm score were used to assess the subjective knee function restoration. The objective laxity test was performed by using the KT-2000 arthrometer (MEDmetric Corp, San Diego, CA, USA) and the side to side difference in displacement was recorded under manual maximum laxity test (23). In order to compare gait kinematics between left and right knees of healthy people, 18 healthy people were also recruited. A portable optical tracking system (3,13) was used to measure the 6 DOF kinematics of the single-bundle ACLR knees, the ACLI contralateral normal knees and the knees of healthy people during treadmill gait (*Figure 1*). The range of motion (ROM) of each DOF was also calculated. Then, the comparison of 6 DOF kinematics and ROM of 6 DOF kinematics were performed between ACLR knees and ACLI contralateral normal knees. The comparison of 6 DOF kinematics between left and right knees of healthy people was also performed.

Surgical procedure and postoperative rehabilitation

The surgical procedures were completed by Dr. DYC, Dr. ZHX and Dr. XQX. The arthroscopic exploration and debridement were performed through the AM and anterolateral (AL) portal. Simultaneously, meniscal tear was diagnosed and treated either by partial resection or suture. The autologous peroneus longus tendon was harvested and knitted to serve as the ACL graft. The femoral tunnel aperture and tibial tunnel aperture were created separately. The tibial tunnel aperture was drilled with use of tibial tunnel guide, based on the ACL anatomical tibial footprint. Then the femoral tunnel aperture was drilled with the AM portal technique. The interference screw was used for the femoral side and tibial side autograft fixation. Finally, the wounds would be closed if the knee stability and graft tension met the surgeon's satisfaction.

In order to alleviating knee swelling and pain, the ice compress was applied after surgery, immediately. The knee was immobilized in full extension with a brace in the early phase. Within 4 weeks, patients were encouraged to perform ankle pump exercise, isometric quadriceps and hamstring contractions, straight and side leg raising exercises. The non-weight bearing knee flexion exercise was performed to improve the ROM from the second week. The gradual-increasing weight-bearing exercise was allowed by at least 4 weeks and full weight-bearing exercise was permitted from 6 weeks. Running and swimming was permitted until 3 months, but contact sports were not suggested until 12 months after operation.

Tunnel placement determination and distribution

All patients were scanned by a CT scanner (GE Discovery CT 750 HD, GE Medical Systems) in the supine position with knees extended and thighs horizontal and parallel. Axial images (120 kV, tube voltage; 185 mAs/slice, tube current; 0.426, pitch factor; 512×512, matrix; 0.625 mm, reconstruction thickness) of the knee were obtained. The 3D model of distal femur and proximal tibia were reconstructed by RadiAnt DICOM Viewer^{TM} (Medixant, Poznán, Poland). For femoral tunnel placement, on the distal view, the medial femoral condyle was cut off along the highest point of intercondylar notch, then the model was rotated to show the medial side of lateral condyle. The Bernard quadrant method (24) was used to measure the femoral tunnel position (*Figure 2A*). For tibial tunnel placement, the method described by Amis *et al.* (25) (*Figure 2B*) was used. The distribution of the centers of femoral tunnel aperture was displayed in *Figure 2C*. Xu *et al.* (26) described the standard area of anatomical ACL femoral footprint center as a circle (*x*, *y*; 27.53%±4.58%, 35.85%±9.2%). In this study, the centers of femoral tunnel aperture within the standard area were defined as anatomical reconstruction group (AR group, n=13), while the centers outside the standard area were defined as Non-anatomical reconstruction group (Non-AR group, n=21). The position of the centers of tibial tunnel aperture was 35.0%±4.6% (95% CI: 33.3–36.6%). In this study, the centers of all included tibial tunnel aperture were within the anatomical ACL tibial footprint (*Figure 2D*).

Graft orientation measurement

For ACL graft orientation measurement, the 3D model of distal femur and proximal tibia were reconstructed by the Mimics 17.0 software (Materialise N.V., Heverlee, Belgium). The geometric center of femoral and tibia tunnel aperture was determined. Then, a cylinder connecting the femoral tunnel center and the tibial tunnel center was constructed to simulate the ACL graft. The long axis of cylinder was used to measure the graft orientation relative to the tibial plateau on coronal and sagittal plane as described by Scanlan *et al.* (27) (*Figure 3*).

Gait kinematics acquisition

The gait kinematics was acquired by an optical tracking system (Opti-Knee, Innomotion Inc., Shanghai, China) while walking on a treadmill at the speed of 3.0 km/h (*Figure 4*). The lower limb anatomic bone markers and infrared-light reflecting rigid bodies were prepared following a previously published protocol (3). Two rigid bodies, with each body comprising four infrared light-reflecting markers (OK_Marquer; Innomotion Inc), were separately fixed in the thigh and shank with bandages. The femoral and tibial anatomical landmarks (i.e., greater trochanter, lateral epicondyle, medial epicondyle, lateral tibia plateau, medial tibia plateau, medial malleolus, lateral malleolus) were identified by a handled digitizing probe with four infrared light-reflecting markers. After a 5-min treadmill gait warm-up, fifteen seconds of kinematics data were obtained by an integrated two-head stereo-infrared camera at 60 Hz, while an integrated synchronous high-speed camera was used to capture the walking video for further gait cycle segmentation. Raw kinematics data was smoothed by a low-pass filter at a frequency of 6 Hz. The rotational and translational parameters (6 DOF) of knee kinematics were calculated based on the coordinate system of the tibia relative to the femur (*Figure 5*). The translation parameter was defined as the displacement of the origin of tibial coordinate system relative to the femoral coordinate system, including anterior (+)/posterior translation, proximal (+)/distal translation and medial/lateral (+) translation. Similarly, the rotational parameter was defined as the tibial coordinate system relative to the femoral coordinate system along the anterior-posterior, medial-lateral and proximal-distal axis in the Euler angle sequence, including varus/valgus (+), internal/external (+) rotation, flexion (+)/extension. The ensemble average curve of each DOF was generated by using GraphPad Prism 8 (GraphPad Software, Inc., USA). Gait cycle segmentation was defined by a kinematic approach (28) mainly including a stance phase and a swing phase.

Statistical analysis

Descriptive statistics was used to summarize the data. All data were described as Means and standard deviations, excepting for the manual maximum laxity, IKDC and Lysholm scores using Means and 95% CI. Before statistical analysis, all data were tested for normality distribution and homogeneity of variance. Normality distribution was checked with Shapiro-Wilk test, and the homogeneity of variance was tested by Levene statistic. Then the unpaired *t*-test, Welch's *t*-test and Mann-Whitney U test were applied according to the result of normality distribution and homogeneity of variance. Statistical analysis was performed with IBM SPSS Statistics 16 (IBM Corporation, NY, USA). Baseline characteristics of two groups were tested with Chi-square (χ^2) test. A value of $P<0.05$ was considered to be statistically significant for all tests.

The statistical parametric mapping (1d nonparametric unpaired *t*-test) was used to examine the difference of kinematics between ACLR knees and contralateral normal knees and the left and right knees of normal populations were compared with the same method. SPM1D package available for Matlab (v.0.4, http://www.spm1d.org) was used. SPM1D uses Random Field Theory expectations regarding smooth, one-dimensional (random) Gaussian fields to make statistical inferences regarding a set of 1D measurements. More details about SPM1D were published in a previous

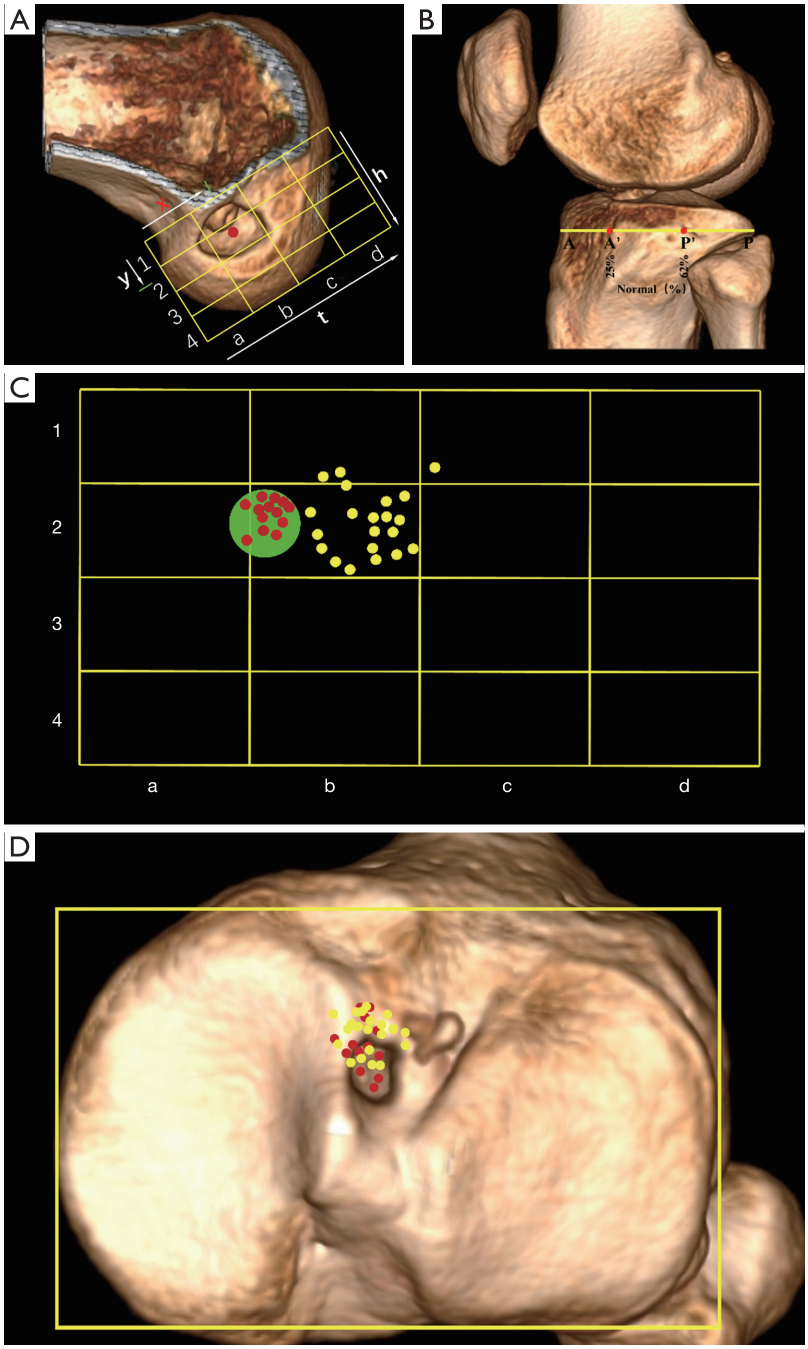

Figure 2 Femoral and tibial tunnel position determination. (A) The center (red point) of femoral tunnel aperture was measured by Bernard quadrant method (4×4 grid). The tunnel position was calculated as (x/t%; y/h%); (B) tibial tunnel position was measured by the method described by Amis *et al.* (25). the anatomical tibial footprint (A'P') was within 25–62% (anterior to posterior); (C) the distribution of femoral tunnel center of all included patients. The green circle represented the standard area of anatomical femoral footprint center described by Xu *et al.* (26). The red points within the green circle represented the anatomical femoral reconstruction, the yellow points outside the green circle represented the non-anatomical femoral reconstruction; (D) the corresponding tibial tunnel distribution. The color of the points was in accordance with the femoral tunnel. t, total sagittal distance of lateral condyle along Blumensaat's line; h, maximum intercondylar notch height perpendicular to Blumensaat's line; x, distance from the center to proximal border line; y, distance from the center to Blumensaat's line; A, anterior; P, posterior.

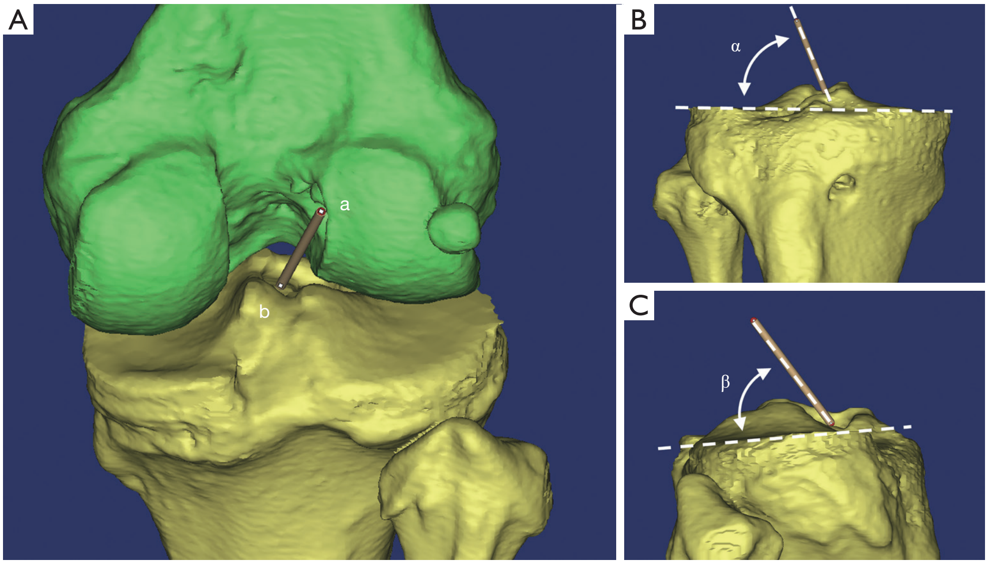

Figure 3 The measurement of graft orientation between the simulated ACL graft and tibial plateau on the coronal and sagittal plane. (A) 3D model of the knee with a cylinder simulating the ACL graft from the back view; (B,C) the graft orientation was defined as the angle between the long axis of ACL graft and tibial plateau projected in coronal (α) and sagittal plane (β). ACL, anterior cruciate ligament; a, the center of femoral tunnel aperture; b, the center of tibial tunnel aperture.

study (29).

Results

Demographics, surgical findings and clinical evaluations of two groups

In total, 34 patients (AR group, n=13; Non-AR group, n=21) and 18 healthy people were recruited. The two groups were comparable in terms of sex, age, height, weight, BMI and follow-up time (*Table 1*). Moreover, the initial status of knee injuries and treatment to meniscal injuries were also comparable between the two groups (*Table 1*). No statistically significant differences were observed between two groups in terms of post-operative IKDC subjective score, Lysholm score (*Figure 6A*) and manual maximum laxity test by KT-2000 (*Figure 6B*) at follow up time.

Graft orientation

For AR group, the mean graft angle on coronal plane was 71.4°±7.2°, and the mean graft angle on sagittal plane was 60.4°±7.5°. For Non-AR group, the mean graft angle on coronal plane was 75.6°±8.0°, and the mean graft angle on sagittal plane was 56.8°±7.5° (*Table 2*).

Gait kinematics and ROM

During the entire gait cycle, no statistically significant differences were observed in kinematics between left and right knees of healthy people (*Figure 7*), confirmed by SPM1D analysis. Moreover, neither the AR group (*Figure 8*) nor the Non-AR group (*Figure 9*) exhibited statistically significant differences in kinematics between the ACLR knees and the corresponding contralateral normal knees. For AR group, there were no statistically significant differences between the contralateral normal knees and ACLR knees in terms of ROM of 6 DOF (*Table 3*). For Non-AR group, the ROM of anterior-posterior translation of the ACLR knees was significantly larger than that of the corresponding contralateral normal knees (1.8±0.6 *vs.* 1.3±0.5 cm; P=0.0080). No statistically significant differences were observed in ROM of the other 5 DOF between the ACLR knees and the corresponding contralateral normal knees (*Table 4*).

Discussion

In our study, there were no statistically significant differences between left and right knees of healthy people in terms of gait kinematics. So, the gait kinematics between

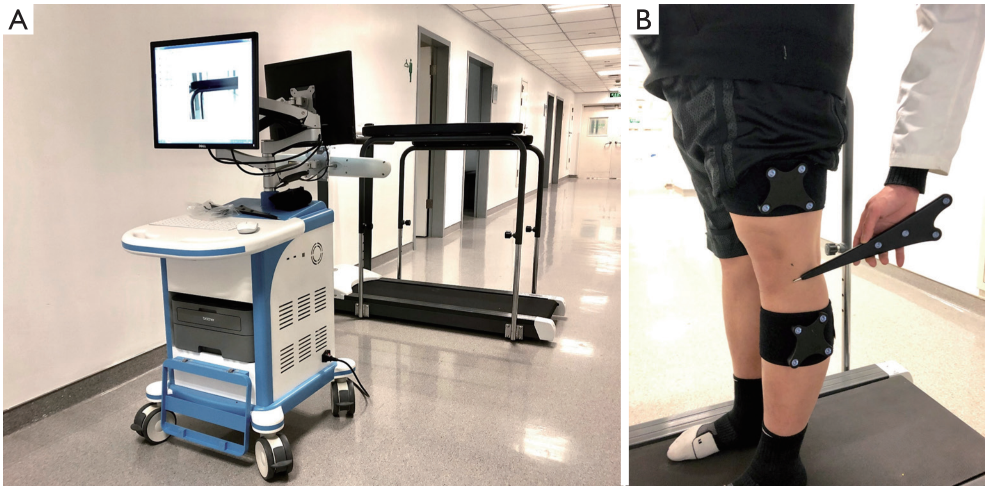

Figure 4 Gait kinematics acquisition procedure. (A) The 3D knee kinematics analysis instrumentation; (B) identification of the femoral and tibial anatomic bone markers with an infrared light reflecting probe to setup knee local coordinate systems before kinematics data collection.

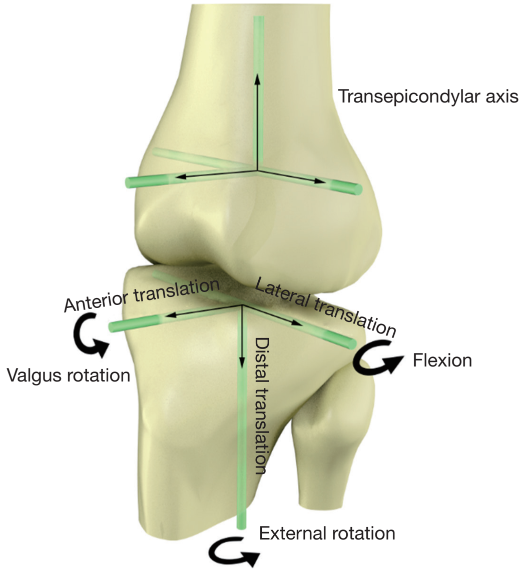

Figure 5 Definition of femoral and tibial coordinate system. The midpoint of transepicondylar axis was defined as the origin of femoral coordinate system. A line crossing the transepicondylar axis was defined as the medial-lateral axis. The anterior-posterior axis was perpendicular to the plane composed of the transepicondylar axis and greater trochanter. The proximal-distal axis was perpendicular to the other two axes. The origin of tibial coordinate system was defined as the center of the line combining the most medial and lateral points of tibial plateau. A line crossing the medial-lateral tibial plateau line was defined as the medial-lateral axis. The anterior-posterior axis was perpendicular to the plane composed of the medial-lateral axis and lateral malleolus. The proximal-distal axis was perpendicular to the other two axes.

ACLR knees and contralateral normal knees of patients were comparable. Our results showed that the AR group exhibited no statistically significant differences in terms of kinematics and ROM of 6 DOF between the ACLR knees and contralateral normal knees during level walking. For Non-AR group, the ACLR knees exhibited significant ROM of anterior-posterior translation by approximately 0.5 cm than contralateral knees.

The results observed in our study were consistent with some other reports (30-33), exhibiting improved locomotion and function restoration after ACLR. Papageorgiou *et al.* (30) examined kinematics of ten cadaveric knees using a robotic/universal force-moment sensor testing system. They found that the varus rotation and internal tibial rotation were restored compared with intact knees after ACLR under a combined 134-N anterior and 200-N axial compressive tibial load. Georgoulis *et al.* (33) tested 13 patients with ACL deficient knees, twenty one patients with ACLR knees and ten control subjects with uninjured knees during walking using a 3D optoelectronic gait analysis system. They found that the ACLR knees can maintain tibial rotational stability. Iliopoulos *et al.* (32) summarized that nearly normalized locomotion economy was observed in anatomical ACLR with either hamstrings tendon or bone-patellar tendon-bone graft during flat, uphill, and downhill walking. Akpinar *et al.* (34) concluded no significant difference of knee kinematics was observed between anatomic ACLR knees and native knees at 24-month follow-up during downhill running. As was consistent with previous studies

Table 1 Demographic data and initial surgical findings of two study groups

Characteristic	AR (n=13)	Non-AR (n=21)	Significance
Sex, male/female, n	9/4	16/5	0.6549
Age, y (mean ± SD)	33±6	31±7	0.3851
Height, cm (mean ± SD)	174±7	175±6	0.8008
Weight, kg (mean ± SD)	77±17	77±16	0.9291
BMI (mean ± SD)	25±4	25±4	0.8546
Follow-up time, mo (mean ± SD)	9±4	10±4	0.1003
Status, n			0.9931
Isolated ACL injuries, n	3	5	
ACL and medial meniscus injuries	2	4	
ACL and lateral meniscus injuries	6	9	
ACL and both menisci injuries	2	3	
Treatment of meniscus injuries, n			0.1261
Meniscus suture	8	8	
Partial resection	2	8	

AR, anatomical reconstruction; Non-AR, non-anatomical reconstruction; ACL, anterior cruciate ligament.

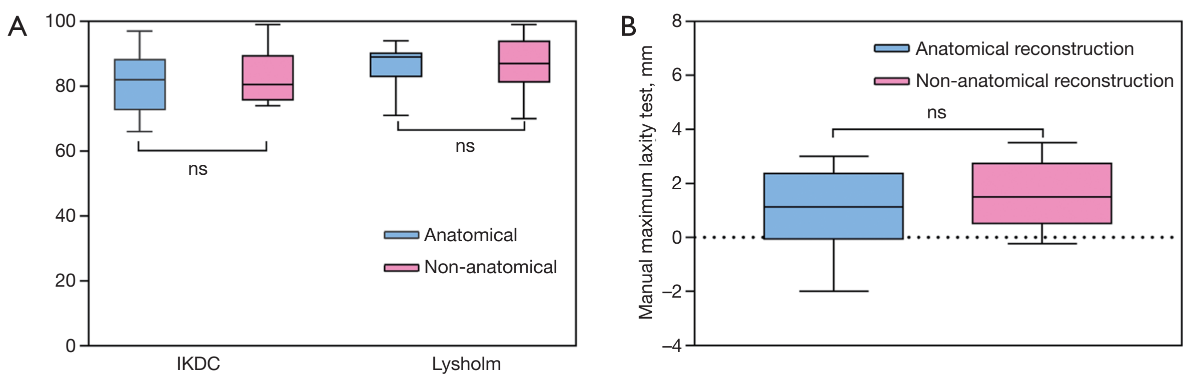

Figure 6 The outcomes of IKDC, Lysholm Score and manual maximum laxity test. (A) The post-operative IKDC and Lysholm score of two groups at follow up time; (B) the post-operative manual maximum laxity test by KT-2000 of two groups at follow up time. The upper and lower bound of the box represented 95% CI. ns, non-statistical significance; IKDC, International Knee Documentation Committee.

Table 2 The ACL graft orientations on the coronal and sagittal plane

Category	ACL graft	
	AR (n=13)	Non-AR (n=21)
Coronal plane	71.4°±7.2°	75.6°±8.0°
Sagittal plane	60.4°±7.5°	56.8°±7.5°

Data were reported as mean ± standard deviation. ACL, anterior cruciate ligament; AR, anatomical reconstruction; Non-AR, non-anatomical reconstruction.

(32,34), our results also showed that anatomical ACLR can restore knee kinematics during level walking. However, as was demonstrated by *Figure 9*, the non-anatomical ACLR in our study can also restore knee kinematics during level walking. This phenomenon may be potentially explained by the following reasons. As was displayed in *Figure 2C*, the centers of non-anatomical tunnel aperture located closely to the standard anatomical area indicating minor discrepancy of placement. Williams *et al.* (35) tested the pre-surgery

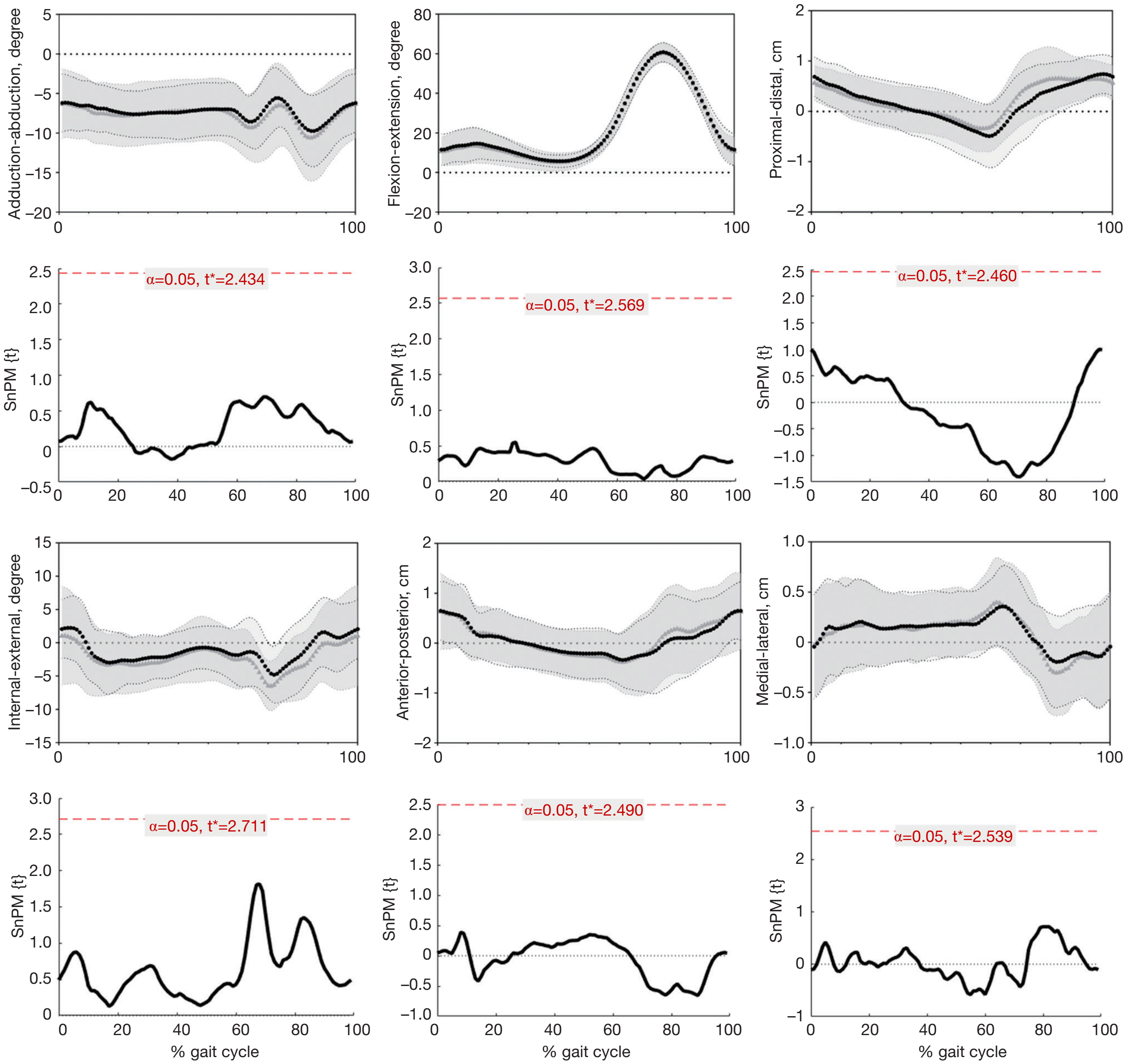

Figure 7 The ensemble average curve of DOF and SPM1D analysis results of left (dashed black circle lines) and right (dashed grey triangle lines) knees of healthy people. The grey shadow represented standard deviation. The SPM1D analysis results indicated no statistically significant differences between left and right knees, where the SnPM values below the dashed red lines (alpha level threshold of 0.05). DOF, degrees of freedom.

to post-surgery ipsilateral comparisons of neuromuscular function after ACLR. They found that the improvement of voluntary muscle control occurred in most muscles after ACLR. The anterolateral ligament (ALL) of knee has been considered to play a potential role in maintaining the knee rotational stability (36) together with ACL and protective effect on ACLR (37). Thus, the compensation from improved voluntary muscle control and native ALL may counteract the minor discrepancy of tunnel location. In our study, the majority of tunnel apertures were located within the area of 25–50% (*x*) of distance *t* and 25–50% (*y*) of distance *h* (*Figure 2C*). This area can be assumed as

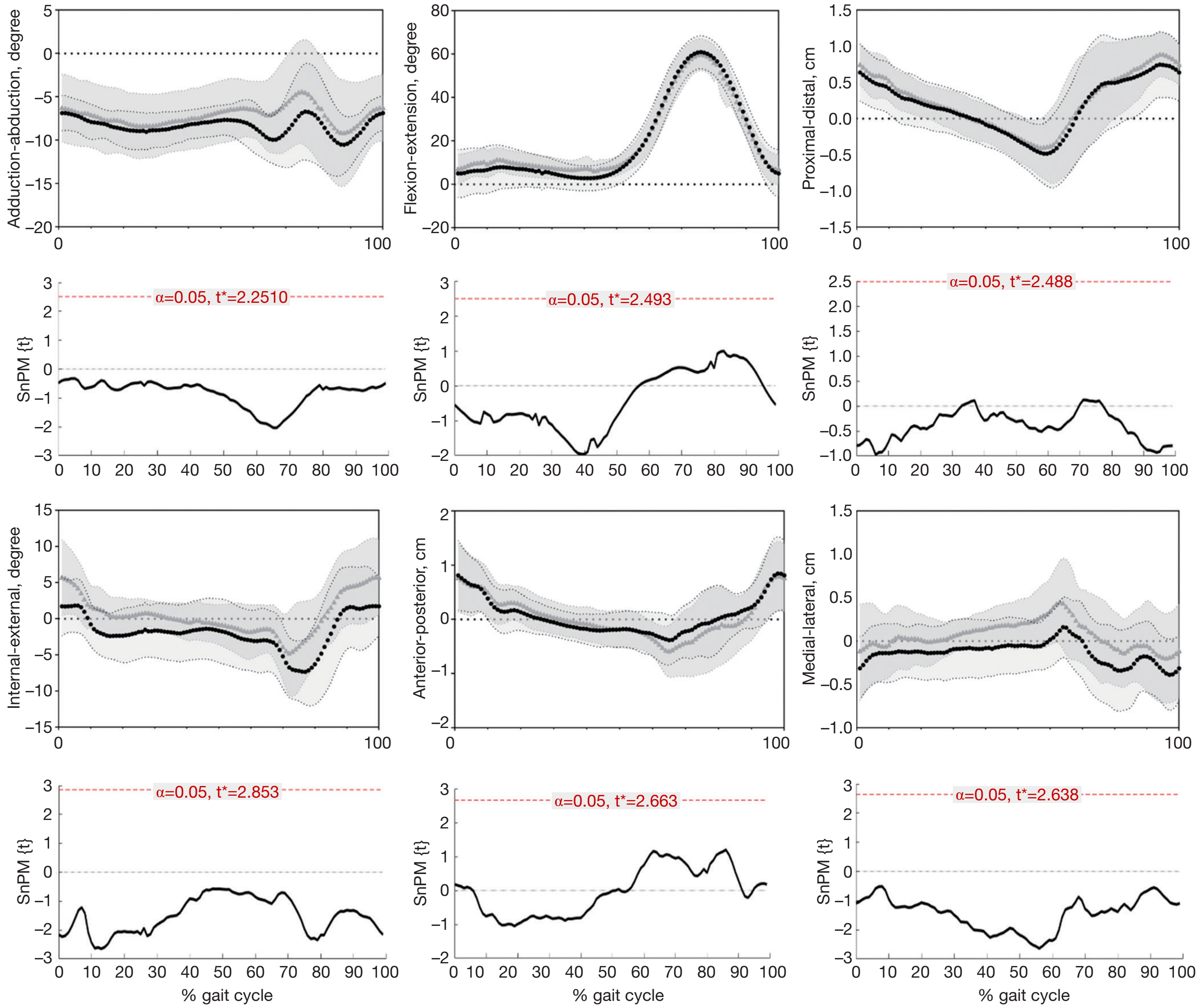

Figure 8 The ensemble average curve of DOF and SPM1D analysis results of contralateral normal knees (dashed black circle lines) and ACLR knees (dashed grey triangle lines) after anatomical ACL reconstruction. The grey shadow represented standard deviation. The SPM1D analysis results indicated no statistically significant differences between contralateral normal knees and ACLR knees, where the SnPM{t} values below the dashed red lines (alpha level threshold of 0.05). DOF, degrees of freedom.

an acceptable region for femoral tunnel aperture in gait kinematics perspective. Of course, more cases should be further included to verify this assumption.

Compared with non-anatomical reconstruction group, the ACL graft orientation of anatomical reconstruction group was closer to the reported native ACL orientation (38) either in coronal plane or sagittal plane, thus better simulating the native ACL fibers to function in terms of graft orientation. Vignos *et al.* (39) reported that the non-anatomic graft geometry was associated with the asymmetric knee kinematics and cartilage contact pattern. As shown in our results, the AR group can restore ROM of 6 DOF, while, in Non-AR group, the ROM of anterior-posterior translation of ACLR knees was significantly larger than that of contralateral knees by approximately 0.5 cm, thus potentially leading to the alterations of cartilage contact pattern and joint congruence. The *in vitro* and animal studies have demonstrated that cartilage degeneration can

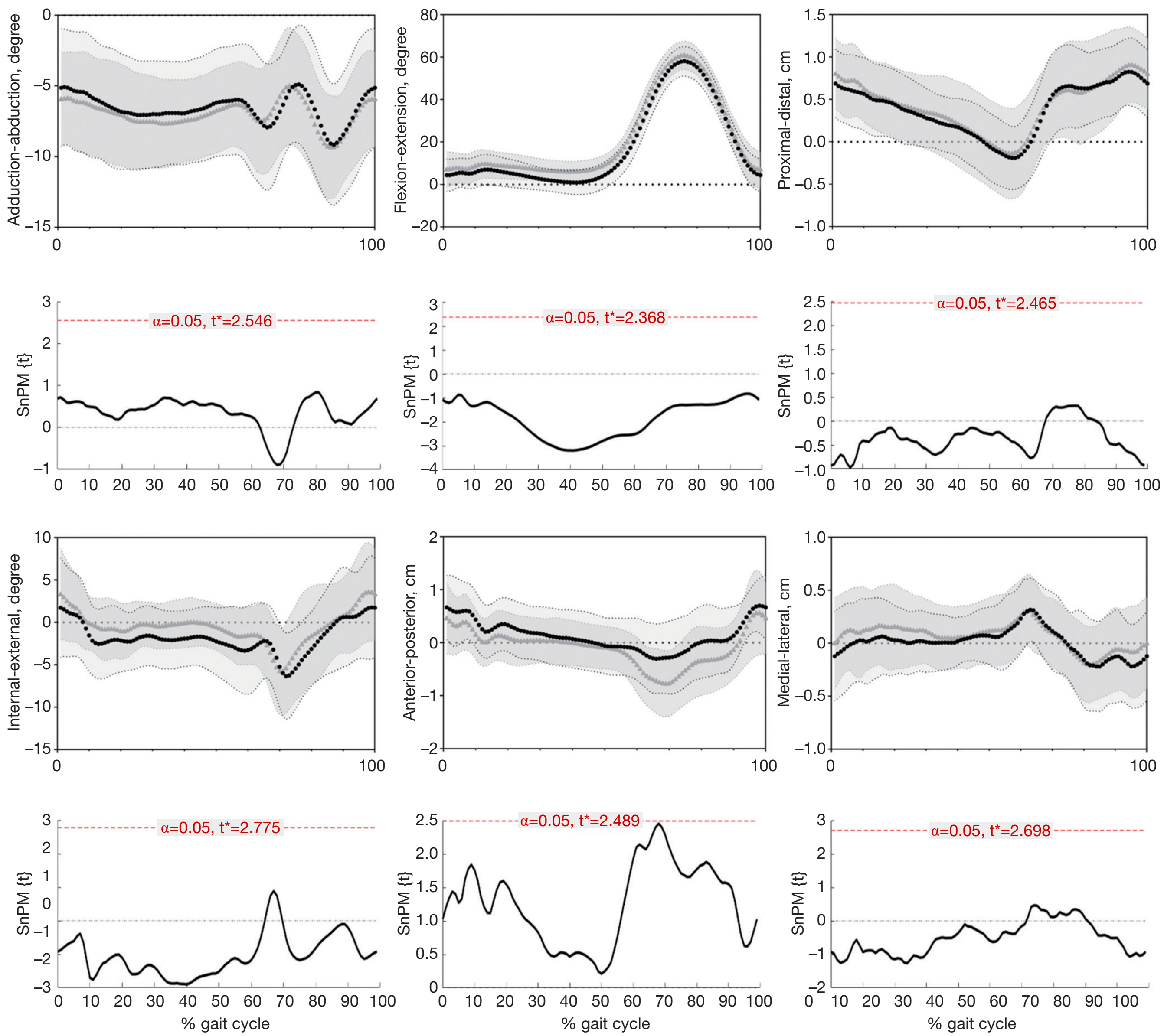

Figure 9 The ensemble average curve of DOF and SPM1D analysis results of contralateral normal knees (dashed black circle lines) and ACLR knees (dashed grey triangle lines) after Non-anatomical ACL reconstruction. The grey shadow represented standard deviation. The SPM1D analysis results indicated no statistically significant differences between contralateral normal knees and ACLR knees, where the SnPM{t} values below the dashed red lines (alpha level threshold of 0.05). DOF, degrees of freedom; ACLR, anterior cruciate ligament reconstruction.

be initiated by the alterations of cartilage mechanics (40,41). Furthermore, Marchant *et al.* (6) reported that the non-anatomic tunnel placement prevailed among the knees of failed or revision ACLR.

However, some studies have reported that kinematics alterations may be one of the possible reasons for subsequent joint degenerations after ACLR, even though the static anterior stability was maintained (17,42,43). There were some studies on kinematics of knees after ACLR, under various loading conditions. Yoo *et al.* (44) tested the effect of ACLR on knee kinematics, using eight human cadaveric knees on a robotic testing system. Their

Table 3 ROM in 6 DOF of patients with anatomical reconstruction

6 DOF	Contralateral knees	ACLR knees	Levene statistic	P value
VR/VL (°)	9.7 (2.4)	9.7 (3.3)	0.805	0.9941
IR/ER (°)	14.4 (2.5)	15.1 (5.3)	13.191	0.6708*
F/E (°)	60.2 (5.4)	55.9 (5.6)	0.002	0.0561
A/P (cm)	1.5 (0.6)	1.7 (0.8)	0.227	0.5430
P/D (cm)	1.4 (0.4)	1.5 (0.3)	0.095	0.6514
M/L (cm)	0.9 (0.3)	0.9 (0.4)	2.270	0.9389

Data were reported as mean (standard deviation). *, Welch's *t*-test. ROM, range of motion; DOF, degrees of freedom; ACLR, anterior cruciate ligament reconstruction; VR/VL, varus/valgus; IR/ER, internal/external rotation; F/E, flexion/extension; A/P, anterior/posterior translation; P/D, proximal/distal translation; ML, medial/lateral translation (the same below).

Table 4 ROM in 6 DOF of patients with non-anatomical reconstruction

6 DOF	Contralateral knees	ACLR knees	Levene statistic	P value
VR/VL (°)	8.0 (2.6)	8.4 (2.6)	0.037	0.6311
IR/ER (°)	12.6 (3.0)	13.6 (4.7)	6.273	0.4398*
F/E (°)	59.1 (5.1)	57.9 (7.1)	4.612	0.5171*
A/P (cm)	1.3 (0.5)	1.8 (0.6)	0.673	0.0080
P/D (cm)	1.2 (0.3)	1.3 (0.5)	3.553	0.5210#
M/L (cm)	0.9 (0.4)	0.9 (0.4)	0.001	0.8665#

Data were reported as mean (standard deviation). *, Welch's *t*-test; #, Mann–Whitney U test. The alpha value less than 0.05 was shown in italic. DOF, degrees of freedom; ACLR, anterior cruciate ligament reconstruction; VR/VL, varus/valgus; IR/ER, internal/external rotation; F/E, flexion/extension; A/P, anterior/posterior translation; P/D, proximal/distal translation; ML, medial/lateral translation (the same below).

results showed that rotational stability may not be restored under simulated physiological loading conditions, even though anterior stability achieved clinical satisfaction. Another study evaluated the kinematics of ACLR knees and contralateral normal knees for six patients during downhill running. More external rotation and adduction were observed in ACLR knees, compared with contralateral knees (43). Furthermore, some other studies have also shown the ACLR knees may not maintain normal rotational stability under high demanding activities, such as a combined descending and pivoting activity (45) or single leg weight-bearing lunge (42). However, most of those studies were performed with cadaveric knees, software simulation or under high demanding activities that may lead to the difference of results between our study and their reports.

Some limitations still exist in this study. We used the reported standard area for anatomical ACL footprint rather than the contralateral normal ACL footprint for the determination of tunnel placement. Second, this study was limited to gait kinematics testing at the speed of 3.0 km/h. Advanced kinematics testing under different states of motion should be further evaluated, because the function demanding for ACL fibers may be different. Third, the results in our study can only reflect the early stage gait kinematics after ACLR, with mean follow-up time of nine months for AR group and ten months for Non-AR group. Further studies should be performed to evaluate the gait kinematics after ACLR during different follow-up times. Fourth, different types of meniscal injuries or treatments may result in gait alterations. But more detailed subgroups were not performed due to the limited number of patients in our study. For advanced comprehension of the effect of meniscal injuries or treatments accompanied ACLR on gait kinematics, further studies are required. Finally, the accuracy of acquired data may be limited by this skin marker-based optoelectronic gait analysis system.

Conclusions

The anatomical ACLR can restore close to normal gait kinematics and ROM of 6 DOF kinematics compared with non-anatomical ACLR. The ACL graft after anatomical ACLR simulated native ACL fibers to function in terms of graft orientation.

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Footnote

Conflicts of Interest: The authors have no conflicts of interest to declare.

Ethical Statement: The authors are accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved. The study was approved by the Institutional Review Board of Nanjing Drum Tower Hospital (2019-024-01) and Written informed consent was obtained from the patient for publication of this manuscript and any accompanying images.

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