In vivo kinematics of the knee after discoid lateral subtotal meniscectomy

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Background: The therapeutic effect after discoid lateral subtotal meniscectomy (DLSM) still remains uncertain. The measurement of *in vivo* kinematics is an important approach for the assessment of knee functions and stabilities. The purpose of this study was to test the *in vivo* knee kinematics after DLSM during walking and running.

Methods: Twenty-one patients with unilateral primary DLSM and 21 healthy volunteers were recruited. The 6 degrees of freedom (DOF) kinematics were collected by a portable optical tracking system while walking at the speed of 3.0 km/h or running at the speed of 5.0 km/h. The range of motion (ROM) of each DOF kinematics were also measured. The comparison of 6 DOF kinematics and ROM of 6 DOF kinematics were performed between the affected knees after DLSM and the contralateral normal knees as well as the knees of healthy people. The subjective Lysholm scores were also recorded at the last follow-up time.

Results: All patients reached a minimum follow-up of 5 (9±3) months. No statistically significant differences were observed in kinematics between the affected knees and the contralateral knees either in walking or running status. The kinematics of the affected knees of patients demonstrated no significant differences compared with that of healthy people during walking. For the affected knees, the ROM of proximal-distal translation of the tibia relative to the femur was significantly larger than that of the contralateral knees during walking (1.4±0.4 *vs.* 1.2±0.3 cm; P=0.0418) or running (1.5±0.8 *vs.* 1.2±0.5 cm; P=0.0430).

Conclusions: In consideration of postoperative kinematics and clinical outcomes demonstrated by this study, the DLSM still remained to be a valid treatment method for symptomatic discoid lateral meniscus (DLM) tears that met the surgical indications for DLSM.

Keywords: Discoid lateral meniscus (DLM); meniscus tears; *in vivo*; tibiofemoral kinematics; subtotal meniscectomy

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Introduction

Discoid lateral meniscus (DLM) is a congenital developmental variation of meniscus. The incidence of DLM is not rare especially in Asian populations (1-3). As was reported by the previous studies, there was 3–5% of incidence for Caucasians (2), 15.3% of incidence for Koreans (1) and 16.6% of incidence for Japanese (3). The symptoms caused by symptomatic DLM tears mainly include pain during exercise, loss of motion or typically snapping during knee motion (4). The remaining meniscal tissue can develop into more severe tears if without appropriate treatment (5). Moreover, the meniscal tears are also associated with cartilage degeneration as demonstrated by many clinical or animal studies (6-8).

Recently, although the meniscus-preserving operations including partial meniscectomy with or without meniscal repair were recommended in patients with symptomatic DLM tears (9), the traditional total meniscectomy or meniscal saucerization still remained indispensable due to different tear patterns, tear degrees or neglected severe tears (10). Some studies indicated that the osteoarthritic changes occurred after total meniscectomy or meniscal saucerization in a long-term follow-up (11,12). However, some studies have supported favorable long-term clinical outcomes without obvious radiographic degenerative changes after discoid lateral subtotal meniscectomy (DLSM) in juveniles (13).

Knee kinematics during walking or running, the most common daily activities, are closely related to knee functions and stabilities. Lin *et al.* (14) found the maximal lateral tibial translation and maximal internal tibial rotation in the knees with DLM injury decreased significantly compared to those with lateral ordinary meniscus injury. They concluded the kinematic features of knees with DLM injury were statistically different from those of healthy knees and knees with lateral ordinary meniscus injury. Harato *et al.* (15) elucidated three-dimensional knee kinematics in patients with DLM during gait. They found knee excursions in the sagittal and axial plane were significantly smaller on the symptomatic side than on the asymptomatic side in the DLM group. Shoemaker *et al.* (16) tested the effects of progressive removal of the meniscus on the anterior-posterior force-versus-displacement response of the anterior cruciate ligament (ACL) deficient knee in fresh cadaver specimens. They concluded that the meniscus played an important role in maintaining knee stability and restricting anterior tibial translation. Hosseini *et al.* (17) demonstrated that the concomitant meniscus tears with ACL injury could affect the knee kinematics in a different way compared to the knees with isolated ACL injuries. Moreover, some studies report that abnormal knee kinematics may be one of the possible reasons for joint degenerations (18,19). The alterations of knee kinematics of the tibiofemoral joint lead to imbalance of cartilage contact pattern, thus resulting in subsequent cartilage degeneration (20).

To the best of our knowledge, few studies have been performed to compare knee kinematics between the affected knees after DLSM and the contralateral normal knees as well as the knees of healthy people during walking and running. The purposes of this study included: (I) the comparison of knee kinematics between the affected knees after DLSM and the contralateral normal knees during walking and running; (II) the comparison of knee kinematics between the affected knees after DLSM and the knees of healthy people during walking.

Methods

Study design

After approval from the institutional review board and obtaining informed consent from all patients, we retrospectively reviewed the medical records from 2018 and 2019 of 21 patients who were previously treated with unilateral primary DLSM for symptomatic DLM tears. Twenty-one healthy volunteers were also recruited for kinematics collection. All subjects were absent of ligament injuries or lower extremity deformities. Before the surgery, the patients with symptomatic DLM tears typically complained of pain localizing to the joint line, swelling, catching, locking, giving way and loss of motion. The physical exam presented with joint effusion, pain in deep flexion or squatting, tenderness with palpation at the lateral joint space or classic presentation of snapping and positive McMurray test. The MRI examination was utilized to evaluate tear location, tear pattern and tear degree. The indications for operation included the aforementioned symptoms and MRI findings. At the last follow-up time, all recruited patients were fully recovered without symptoms and the patients and healthy volunteers were brought back as a group to get the data collected.

Surgical procedure and postoperative rehabilitation

Arthroscopy was performed under general anesthesia. The routine anteromedial (AM) portal and anterolateral (AL)

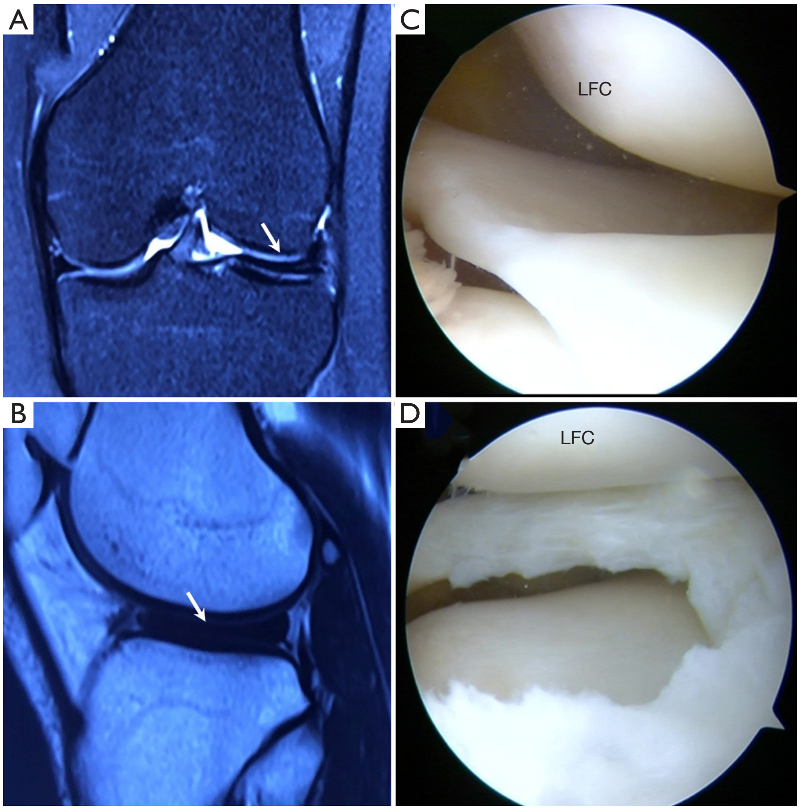

Figure 1 The MRI and arthroscopic findings of DLM and outcomes after DLSM. (A) The magnetic resonance imaging on the coronal plane, the white arrow indicated the DLM; (B) the magnetic resonance imaging on the sagittal plane, the white arrow indicated the DLM; (C) arthroscopic findings of the DLM; (D) the DLSM was performed arthroscopically. DLM, discoid lateral meniscus; DLSM, discoid lateral subtotal meniscectomy; LFC, lateral femoral condyle.

portal for knee arthroscopy were utilized. The standard AL portal was utilized for viewing and the AM portal was used for working. A thorough diagnostic arthroscopy should be implemented to identify all areas of lesions, before any arthroscopic procedures, including discoid lateral meniscal debridement. The knee was placed into flexion and continuous varus stress was applied to the knee, with the leg in the figure-four position, then the lateral compartment was viewed through the AL portal. After determination of DLM tears, the DLSM with the periphery meniscal portion remaining was performed as described by Lee *et al.* (21). Then the wounds would be closed and the ropivacaine was injected into the wound subcutaneously to relieve pain (*Figure 1*).

In order to alleviate knee swelling and pain, the ice compress was applied after surgery, immediately. Patients were encouraged to perform ankle pump exercise as early as possible to prevent the formation of lower limb thrombosis. The isometric quadriceps and hamstring contractions, straight and side leg raising exercises were also encouraged to prevent muscle atrophy. The knee extension and flexion exercise were encouraged to increase the range of motion (ROM) of knee. The initiation of low impact exercises can be completed according to the symptoms of patients, then the followings were increasing impact exercises and jogging. The intense physical exercises were not suggested until 3 months after operation.

Kinematics acquisition

The knee kinematics was acquired by an optical tracking system (Opti-Knee, Innomotion Inc., Shanghai, China) while walking at the speed of 3.0 km/h or running at the speed of 5.0 km/h on a treadmill (*Figure 2*). The lower limb anatomical bone landmarks were recognized manually, and the infrared-light reflecting rigid bodies were wrapped

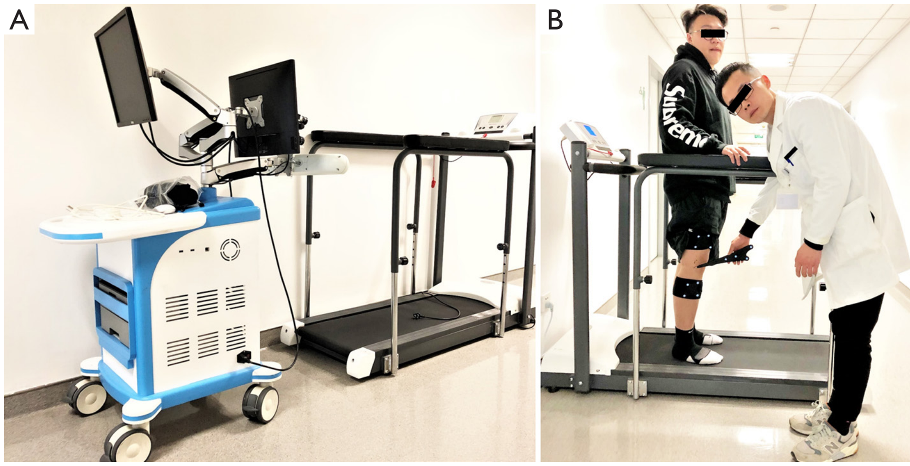

Figure 2 The components of kinematics analysis apparatus and identification of anatomical landmarks. (A) The 3D knee kinematics analysis apparatus; (B) identification of the femoral and tibial anatomical landmarks with an infrared light reflecting probe to setup knee local coordinate systems before kinematics data collection.

around the leg as described by a previously published protocol (22). After a 5-minute treadmill warm-up, an integrated stereo-infrared camera at 60 Hz was used to acquire fifteen seconds of kinematics. Simultaneously, an integrated synchronous high-speed camera was utilized to capture the walking or running video for further gait cycle segmentation. Raw 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 3*). The translational 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 the utilization of MATLAB (2016a; Math-Works Inc.). Cycle segmentation was defined by a kinematic approach mainly including a stance phase and a swing phase (23).

Statistical analysis

The required sample size was computed by a priori power analysis with *t*-test or Mann-Whitney U test using an α level of 0.05, a power of 0.8 and an effect size of 0.8 by using G*Power software (G*Power 3.1.9.2). The necessary sample size for each group was 21 to achieve a power of 0.8. The data were summarized by the descriptive statistics. All data were presented with means and standard deviations (SD). All data were tested for normality distribution and homogeneity of variance, before statistical analysis was performed. The Shapiro-Wilk test was used to verify the normality distribution, and the Levene statistic was applied to test the homogeneity of variance. 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). 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 evaluate the difference of kinematics between the affected knees and the contralateral normal knees of patients. The difference of kinematics between the affected knees of patients and the knees of healthy people was compared with the same method. The SPM1D package available for MATLAB (v.0.4, http://www.spm1d.org) was used. The SPM1D used Random Field Theory expectations regarding smooth, one-dimensional (random) Gaussian fields to make statistical inferences regarding a set of 1D measurements. More details about

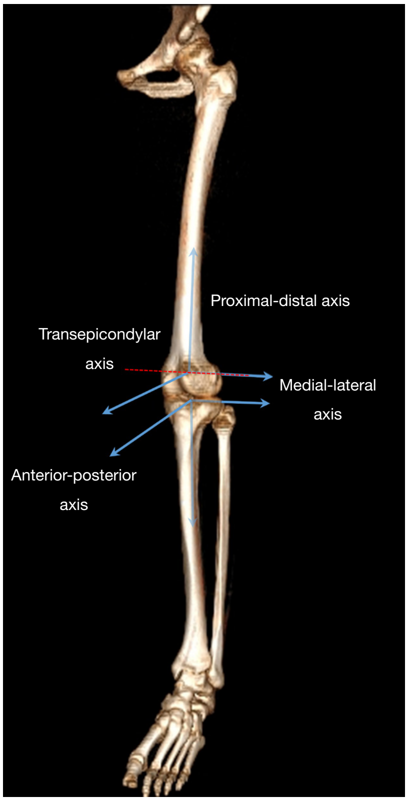

Figure 3 Definition of the femoral and tibial coordinate system. The midpoint of transepicondylar axis was defined as the origin of femoral coordinate system. A line crossing the transepicondylar axis was defined as the medial-lateral axis. The anterior-posterior axis was perpendicular to the plane which was composed of the transepicondylar axis and the 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 which combined 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 which was composed of the medial-lateral axis and lateral malleolus. The proximal-distal axis was perpendicular to the other two axes.

SPM1D were published in a previous study (24).

Results

The demographics of patients and healthy volunteers

The demographic data of the patients and healthy volunteers were described in *Table 1*. Among these 21 patients (21 knees), 11 males and 10 females were included.

Table 1 Demographic data of the patients and healthy people

Parameters	Patients (n=21)	Healthy people (n=21)
Sex, male/female, n	11/10	17/4
Age, y	18±5	26±4
Height, cm	167±9	173±7
Weight, kg	62±16	69±9
BMI	22±4	23±2
Follow-up time, mo	9±3	–
Lysholm score at final follow-up	91±6	–

Data were shown as mean ± SD. BMI, body mass index; SD, standard deviation.

Among the affected knees, 16 left knees and 5 right knees were treated with DLSM. The average age of patients at operation time was 18 (range, 12–29) years. The average follow-up time was 9 (range, 5–12) months after operation. The average subjective Lysholm score was 91 (range, 82–100).

Knee kinematics and ROM of 6 DOF analysis

During the entire kinematics cycle, no statistically significant differences were observed in kinematics between the affected knees after DLSM and the contralateral normal knees either in walking (*Figure 4*) or running (*Figure 5*) status, as was confirmed by SPM1D analysis. Moreover, both lower extremities of healthy people demonstrated excellent consistence in kinematics (*Figure 6*). So, the left knees of healthy people were selected for comparison with the affected knees of patients. The kinematics of the affected knees of patients demonstrated no significant differences compared with that of healthy people during walking (*Figure 7*). The ROM of proximal-distal translation of the affected knees was significantly larger than that of the contralateral normal knees (1.4±0.4 *vs.* 1.2±0.3 cm; P=0.0418) during walking. However, no statistically significant differences were observed in ROM of the other 5 DOF kinematics between the affected knees and the contralateral normal knees during walking (*Table 2*). Similarly, The ROM of proximal-distal translation of the affected knees was significantly larger than that of the contralateral normal knees (1.5±0.8 *vs.* 1.2±0.5 cm; P=0.0430) during running. Nevertheless, no statistically significant differences were observed in ROM of the other 5 DOF kinematics between

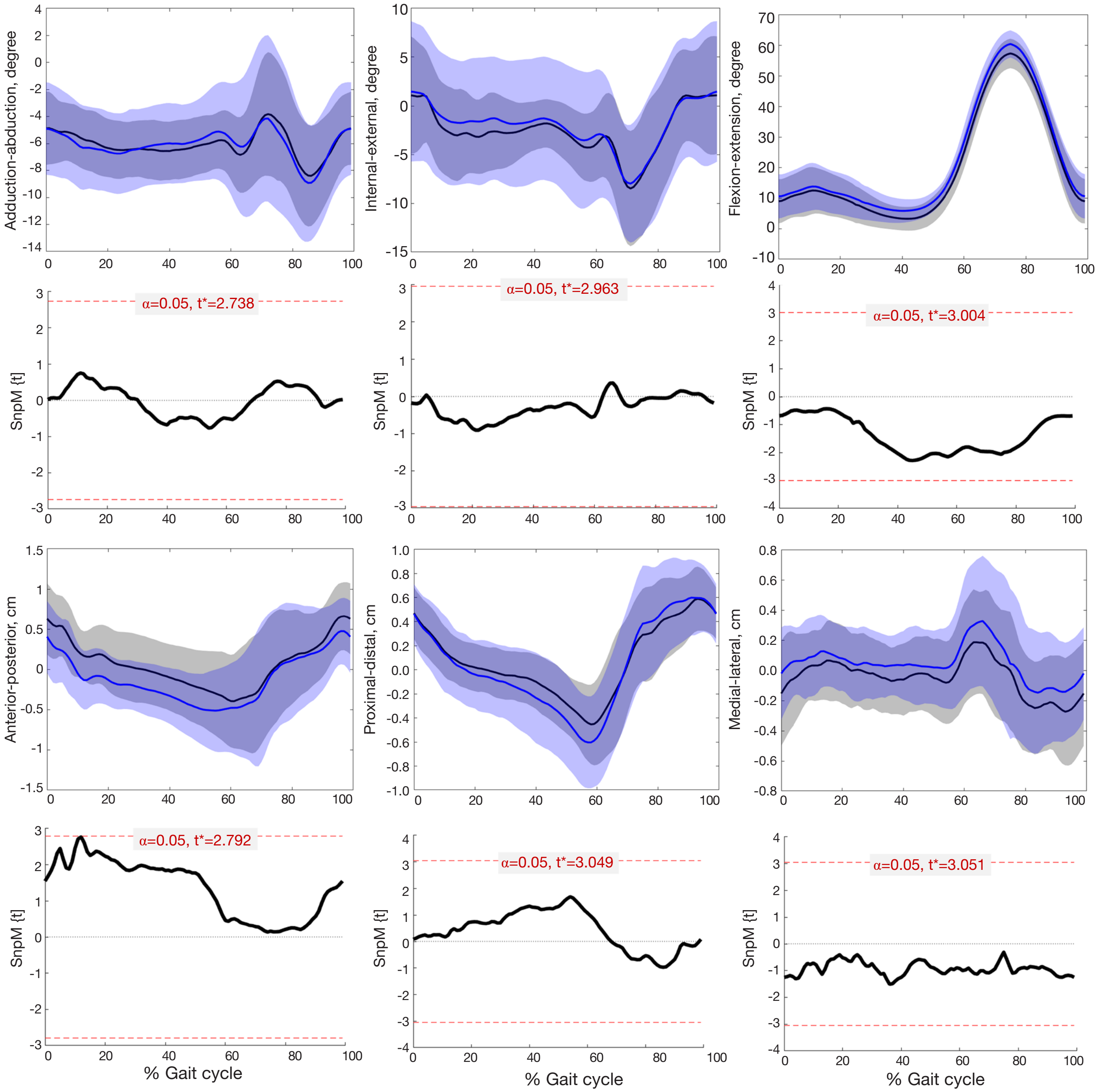

Figure 4 The ensemble average curve of DOF and SPM1D analysis results of the affected knees after DLSM (blue lines) and the contralateral normal knees (black lines) during walking at the speed of 3 km/h. The blue shadow and grey shadow represented SD. The SPM1D analysis results below each ensemble average curve of DOF indicated no statistically significant differences between the affected knees and the contralateral normal knees, where the SnPM{t} values below the dashed red lines (alpha level threshold of 0.05). DOF, degrees of freedom; DLSM, discoid lateral subtotal meniscectomy; SD, standard deviation.

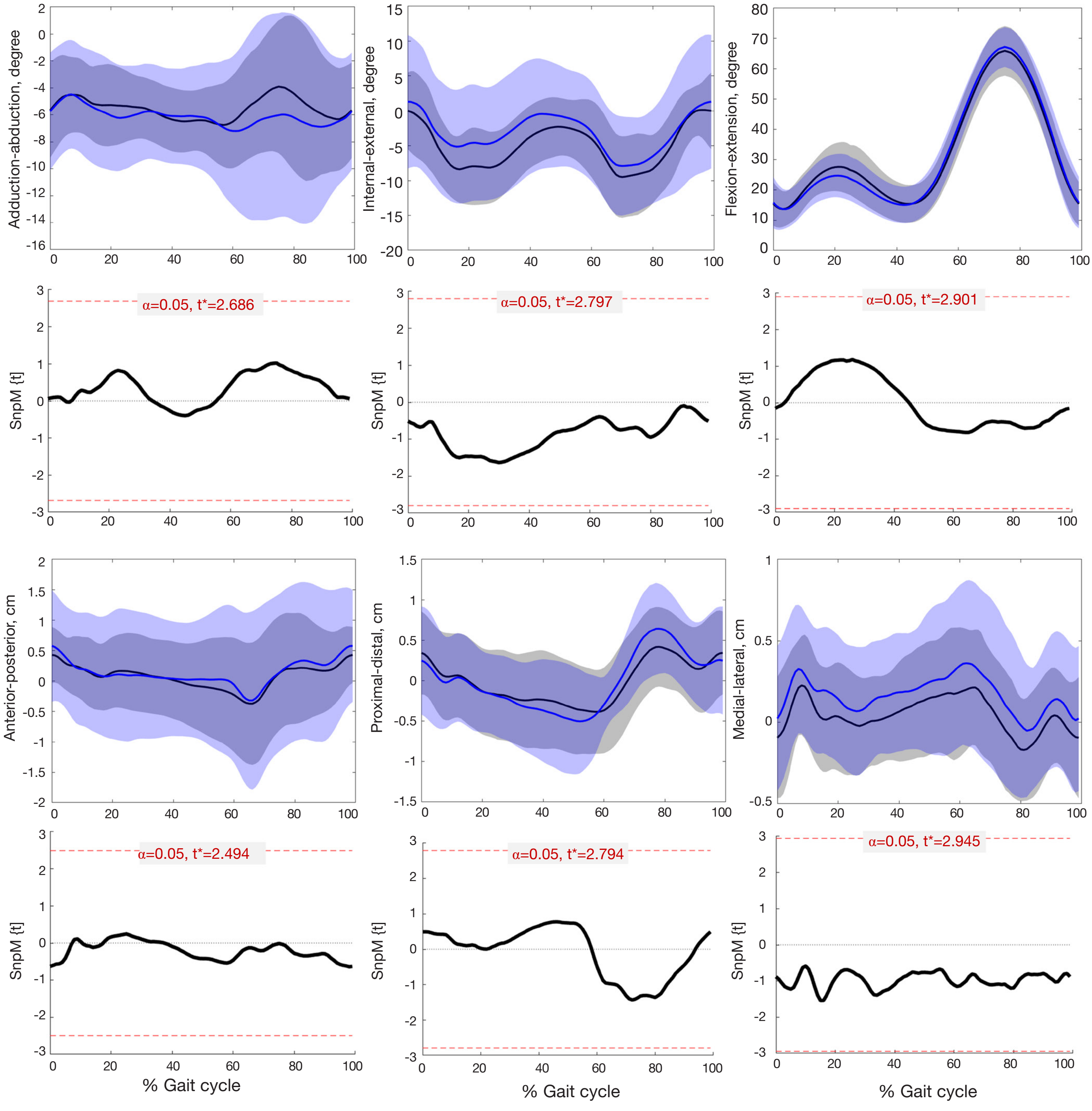

Figure 5 The ensemble average curve of DOF and SPM1D analysis results of the affected knees after DLSM (blue lines) and the contralateral normal knees (black lines) during running at the speed of 5 km/h. The blue shadow and grey shadow represented SD. The SPM1D analysis results below each ensemble average curve of DOF indicated no statistically significant differences between the affected knees and the contralateral normal knees, where the SnPM{t} values below the dashed red lines (alpha level threshold of 0.05). DOF, degrees of freedom; DLSM, discoid lateral subtotal meniscectomy; SD, standard deviation.

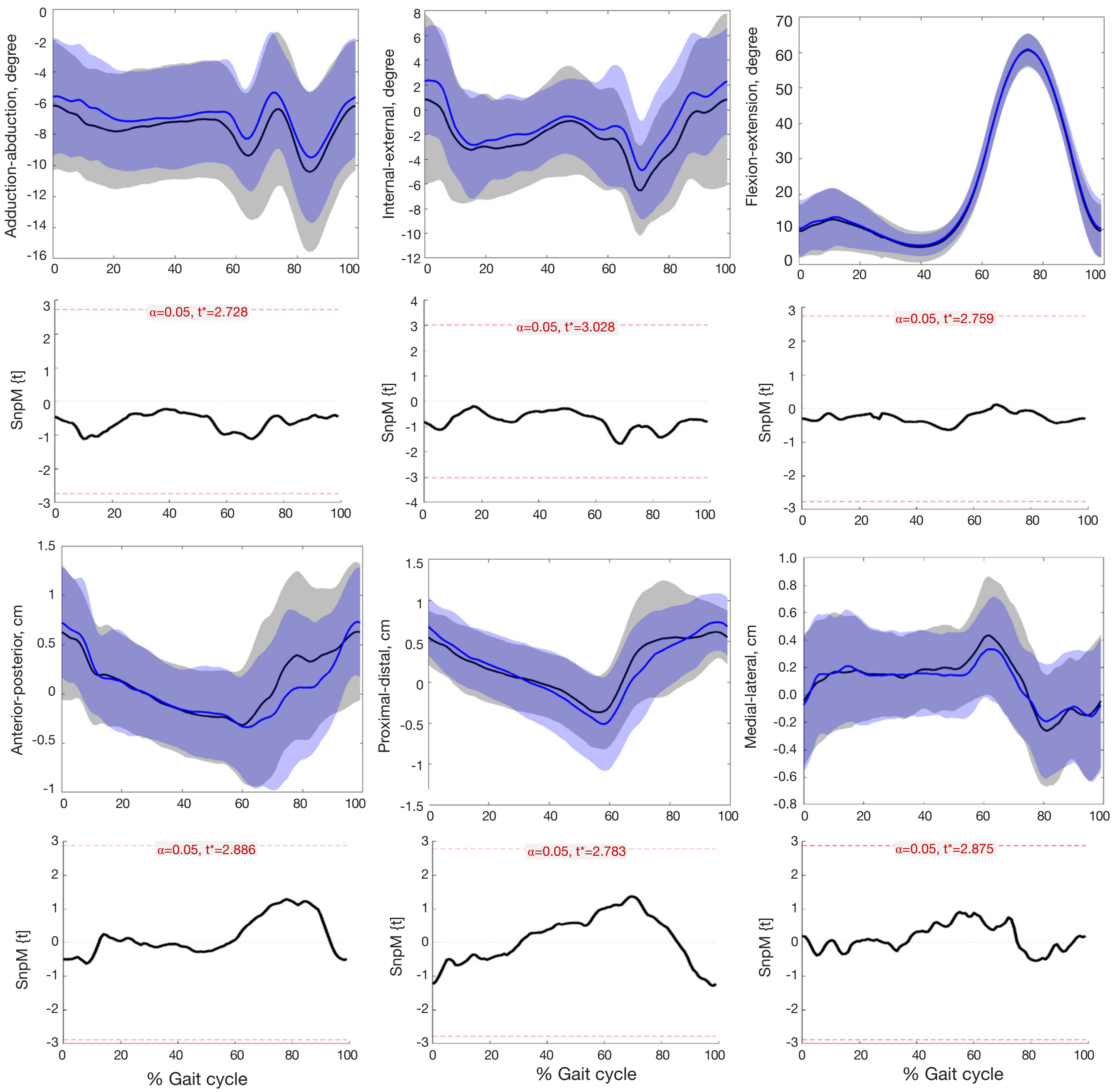

Figure 6 The ensemble average curve of DOF and SPM1D analysis results of the left knees (blue lines) and right knees (black lines) of healthy people during walking at the speed of 3 km/h. The blue shadow and grey shadow represented SD. The SPM1D analysis results below each ensemble average curve of DOF indicated no statistically significant differences between left knees and right knees, where the SnPM{t} values below the dashed red lines (alpha level threshold of 0.05). DOF, degrees of freedom; SD, standard deviation.

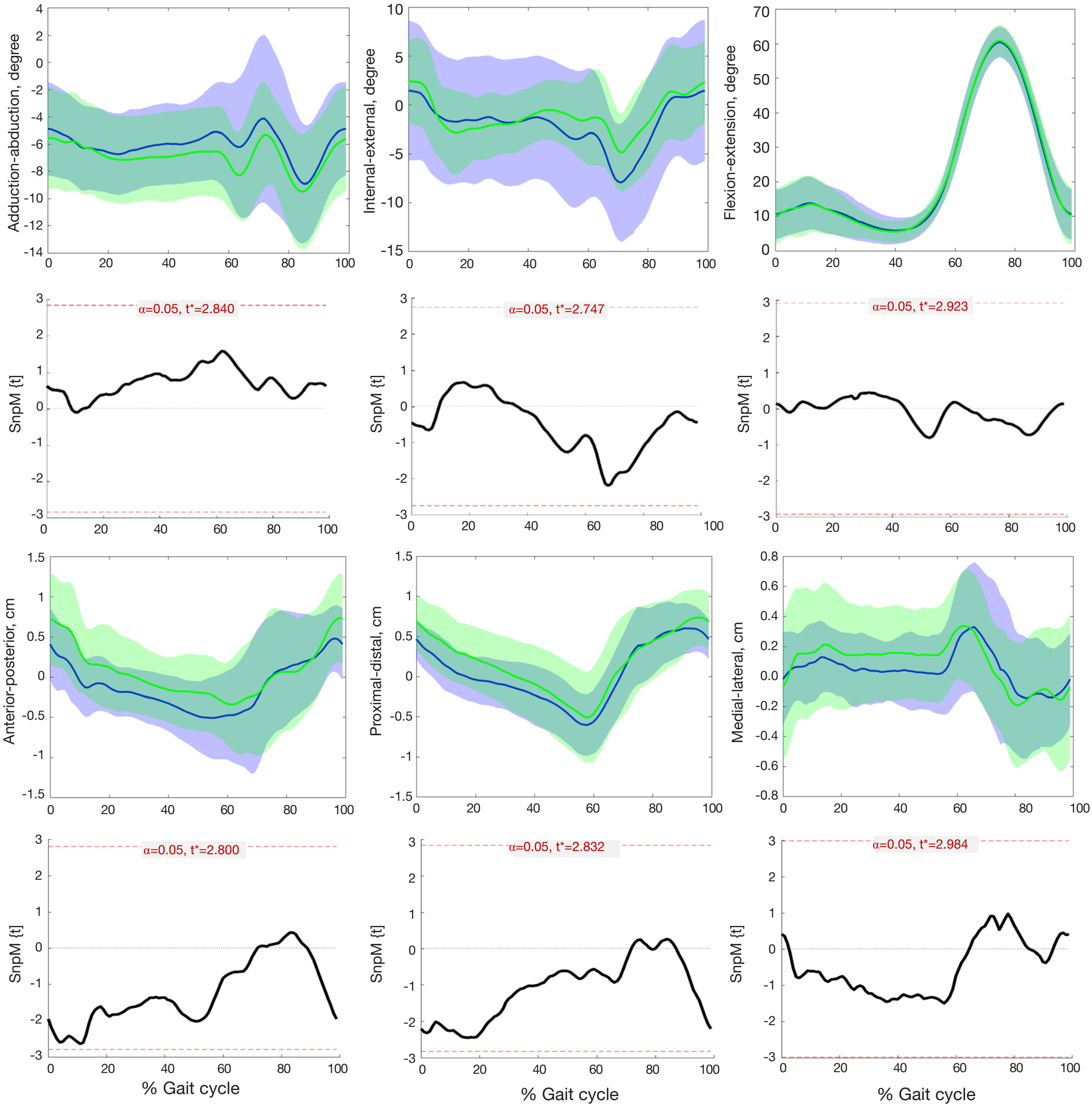

Figure 7 The ensemble average curve of DOF and SPM1D analysis results of the affected knees after DLSM (blue lines) and the knees of healthy people (green lines) during walking at the speed of 3 km/h. The blue shadow and green shadow represented SD. The SPM1D analysis results below each ensemble average curve of DOF indicated no statistically significant differences between the affected knees and the knees of healthy people, where the SnPM{t} values below the dashed red lines (alpha level threshold of 0.05). DOF, degrees of freedom; DLSM, discoid lateral subtotal meniscectomy; SD, standard deviation.

Table 2 Comparison of ROM in 6 DOF between the contralateral knees and the affected knees of patients during walking

6 DOF	Contralateral knees	Affected knees	Levene statistic	P value
VR/VL (°)	8.3 (2.5)	8.4 (3.5)	1.198	0.9047
IR/ER (°)	14.5 (4.8)	13.9 (4.5)	0.022	0.7180#
F/E (°)	55.5 (4.1)	56.3 (4.9)	0.165	0.5820
A/P (cm)	1.4 (0.5)	1.4 (0.5)	0.000	0.6783#
P/D (cm)	1.2 (0.3)	1.4 (0.4)	1.362	0.0418
M/L (cm)	0.8 (0.4)	0.8 (0.2)	0.513	0.7994#

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). #, Mann-Whitney U test. The alpha value less than 0.05 was shown in boldface. ROM, range of motion; DOF, degrees of freedom.

Table 3 Comparison of ROM in 6 DOF between the contralateral knees and the affected knees of patients during running

6 DOF	Contralateral knees	Affected knees	Levene statistic	P value
VR/VL (°)	7.8 (2.3)	8.6 (4.1)	1.299	0.7994#
IR/ER (°)	16.1 (2.7)	15.6 (4.7)	4.153	0.6841*
F/E (°)	53.8 (6.3)	55.9 (5.4)	0.380	0.2632
A/P (cm)	1.3 (0.6)	1.4 (0.5)	0.615	0.5291#
P/D (cm)	1.2 (0.5)	1.5 (0.8)	0.592	0.0430#
M/L (cm)	0.8 (0.3)	0.8 (0.4)	0.505	0.9680#

*, Welch's *t*-test; #, Mann-Whitney U test. The alpha value less than 0.05 was shown in boldface. ROM, range of motion; DOF, degrees of freedom.

the affected knees and the contralateral normal knees during running (*Table 3*). Moreover, there were no significant differences between the affected knees of patients and the knees of healthy people in terms of the ROM of 6 DOF kinematics during walking (*Table 4*).

Discussion

The first important finding of this study is that there is no significant difference in kinematics between the affected knees and the contralateral knees either in walking or running status during the entire kinematics cycle. The second important finding is that the affected knees exhibited significant larger ROM of proximal-distal translation than the contralateral knees by mean 0.2 cm during walking and 0.3 cm during running.

The postoperative knee kinematics were closely related to the restoration of knee functions and stabilities. Moreover, the abnormal knee kinematics have been reported to be associated with subsequent joint deterioration by many clinical and animal studies (18-20). Shekarforoush *et al.* (19) elucidated the relations between kinematics alterations and post traumatic osteoarthritic-like changes in sheep injury models. They concluded that the magnitude of the change in the translation vector would be a risk factor for osteoarthritis. Zheng *et al.* (25) investigated the tibiofemoral skeletal kinematics and cartilage contact arthrokinematics after isolated medial or lateral meniscectomy. They concluded that no consistent difference was observed in skeletal kinematics between the affected knees and the contralateral intact knees, but, significant alterations in the cartilage contact arthrokinematics were demonstrated. As was demonstrated in this study, the affected knees and the contralateral knees presented no significant differences in terms of kinematics. For the affected knees, the average lateral translation of the tibia relative to the femur was greater than that of the contralateral normal knees during waking (*Figure 4*) or running (*Figure 5*) through the entire

Table 4 Comparison of ROM in 6 DOF between the knees of healthy people and the affected knees of patients during walking

6 DOF	Healthy knees	Affected knees	Levene statistic	P value
VR/VL (°)	7.7 (2.8)	8.4 (3.5)	0.238	0.4754
IR/ER (°)	12.0 (4.5)	13.9 (4.5)	0.005	0.2130
F/E (°)	56.4 (5.2)	56.3 (4.9)	0.038	0.9362
A/P (cm)	1.5 (0.6)	1.4 (0.5)	1.780	0.6047
P/D (cm)	1.5 (0.4)	1.4 (0.4)	0.379	0.8944
M/L (cm)	1.0 (0.3)	0.8 (0.2)	1.651	0.1806

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). ROM, range of motion; DOF, degrees of freedom.

kinematics cycle, even though the difference was not statistically significant. Luczkiewicz *et al.* (26) investigated the effect of a change in the meniscal cross sectional shape on the biomechanics of a knee joint. They suggested that the medial-lateral translation of the knee joint can be affected by a change in the meniscal shape in the cross-sectional plane. Thus, the alterations in the meniscal shape after DLSM may explain this mild discrepancy of medial-lateral translation between the affected knees and the contralateral knees. However, it should be further verified whether this mild discrepancy could lead to any clinical consequences, such as cartilage degeneration. As for the ROM of kinematics, the affected knees exhibited significant larger ROM of proximal-distal translation than that of the contralateral knees during waking or running. The alterations in the meniscal structure after DLSM may account for this discrepancy.

Currently, the optional surgical treatments for DLM tears included the total meniscectomy or subtotal meniscectomy (27), partial meniscectomy with or without repair (28) and meniscal allograft transplantation (29,30). For those cases with large complex tears, severe meniscal tissue degeneration caused by delayed diagnosis of DLM, then the total meniscectomy or subtotal meniscectomy was inevitable (27,31). The partial meniscectomy was indicated for central portion tears with stable peripheral rim. The aim for partial meniscectomy was to remove the thickened central portion of meniscus and the unstable torn part with a stable peripheral rim more than 6 mm from capsular attachment remaining (28). Although the meniscal tissue preserved strategy for DLM tears was recommended by many surgeons (32,33), the subsequent knee joint degenerations cannot be prevented completely (4). Some studies have also demonstrated favorable long-term clinical outcomes without apparent radiographic degenerative changes after total meniscectomy or subtotal meniscectomy (34-37). Furthermore, the results of this study have demonstrated that the affected knees after DLSM exhibited kinematics symmetry with the contralateral knees during waking or running. And no significant differences were observed between the affected knees and the knees of healthy people in terms of kinematics during walking. Thus, in consideration of postoperative kinematics and clinical outcomes demonstrated by this study, the DLSM still remained to be a valid treatment method for symptomatic DLM tears that met the surgical indications for DLSM.

Some limitations still exist in this study. First, the limited patient sample would not represent the overall situation of kinematics after DLSM. Second, the results demonstrated in this study can only reflect the early stage kinematics after DLSM, with mean follow-up time of 9 months. In addition, this study was limited to knee kinematics testing during walking at the speed of 3.0 km/h and running at the speed of 5.0 km/h. But, the demanding for function of meniscus was different under different states of motion, such as single-leg jump, ascending or descending stairs. Further studies should be performed to evaluate the kinematics after DLSM during different follow-up times as well as under different states of motion. Third, the assessment of cartilage degeneration and joint osteoarthritis-like changes based on radiography or secondary arthroscopy were absent in the current study. Thus, the relation between the kinematics and the potential joint degenerations could not be further illustrated. Finally, it was also acknowledged that the comparison results may be affected by the measurement errors caused by the apparatus and the significant difference of gender, age and height between the recruited patients and healthy people.

Conclusions

In consideration of postoperative kinematics and clinical outcomes demonstrated by this study, the DLSM still remained to be a valid treatment method for symptomatic DLM tears that met the surgical indications for DLSM.

Acknowledgments

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Footnote

Conflicts of Interest: All authors have completed the ICMJE uniform disclosure form (available at http://dx.doi.org/10.21037/aoj.2020.01.04). QJ serves as an Editor-in-Chief of *Annals of Joint* from Mar 2016 to Feb 2021; DS serves as an unpaid Executive Editor-in-Chief of *Annals of Joint* from Mar 2016 to Feb 2021. The other 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 conducted in accordance with the Declaration of Helsinki (as revised in 2013). The study was approved by Medical Ethics Committee of Nanjing Drum Tower Hospital (No. 2019-161-01). Informed consent was taken from all individual participants.

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