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Internal tibial rotation during in vivo, dynamic activity induces greater sliding of tibio-femoral joint contact on the medial compartment

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Abstract

Purpose Although extensive research has been conducted on rotational kinematics, the internal/external rotation of the tibio-femoral joint is perhaps less important for protecting joint health than its effect on joint contact mechanics. The purpose of this study was to evaluate tibio-femoral joint contact paths during a functional activity (running) and investigate the relationship between these arthrokinematic measures and traditional kinematics (internal/external rotation).

Methods Tibio-femoral motion was assessed for the contralateral (uninjured) knees of 29 ACL-reconstructed individuals during downhill running, using dynamic stereo X-ray combined with three-dimensional CT bone models to produce knee kinematics and dynamic joint contact paths. The joint contact sliding length was estimated by comparing femoral and tibial contact paths. The difference in sliding length between compartments was compared to knee rotation.

Results Sliding length was significantly larger on the medial side (10.2 ± 3.8 mm) than the lateral side (2.3 ± 4.0 mm). The difference in sliding length between compartments (mean 7.8 ± 3.0 mm) was significantly correlated with internal tibial rotation ($P < 0.01$, $R^2 = 0.74$).

Conclusion The relationship between rotational knee kinematics and joint contact paths was specifically revealed as greater tibial internal rotation was associated with larger magnitude of sliding motion in the medial compartment. This could suggest that lateral pivot movement occurs during running.

Clinical relevance Rotational kinematics abnormality should be treated for restoring normal balance of joint sliding between medial and lateral compartments and preventing future osteoarthritis.

Level of evidence Prognostic studies, Level II.

Keywords Dynamic stereo radiography · Knee kinematics · Joint contact · Running activity · Lateral pivot movement

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Introduction

Normal knee joint kinematics has been frequently investigated to establish ideal movement after total knee arthroplasty or knee ligament injury treatment. Most total knee arthroplasty implants were designed to reproduce the medial pivot movement [8, 30, 35, 44], i.e., knee rotation with the rotational axis located on the medial side, based on numerous cadaver studies [9–11, 13, 17, 19, 23, 31, 33, 45]. Recent investigations, however, suggest that medial pivot may not always occur during dynamic, in vivo activity [22, 24]. Findings of abnormal knee rotations after conventional ACL reconstruction [7, 14, 15, 32, 33, 41, 42] and their potential role in the long-term risk of knee degenerative change [5] have also motivated further investigation into the rotational behavior of the healthy knee under dynamic, in vivo loading.

Abnormal rotation is associated with altered joint contact position, which may lead to the development of osteoarthritis [4, 5, 39, 43]. However, most previous studies investigating in vivo joint contact location have been carried out in a series of static positions and have focused on the tibial side only [6, 11, 12, 18, 19, 21, 27, 34, 43]. Thus, they do not fully describe the nature of the joint surface interactions, particularly during dynamic loading.

Tibio-femoral contact movement consists of both rolling and sliding [19]. Since sliding creates much higher shear velocities and associated shear stresses than rolling, quantifying the sliding movement could be valuable for understanding relationships between joint contact kinematics and cartilage degeneration. Since for pure rolling, the lengths of the opposing contact paths (tibia and femur) would be equal, the sliding component of the contact path (joint contact sliding length) can be estimated from the difference between tibial and femoral contact path excursions.

The purpose of this study was to estimate the tibial and femoral joint contact paths during running and to determine the relationship between knee rotation and sliding length. Considering that longer contact paths on the lateral tibial plateau have been observed along with knee rotation [6, 11, 12, 18, 19, 21, 34] and that this "medial pivot" movement is generally acknowledged for total knee arthroplasty design [8–11, 13, 17, 19, 23, 30, 31, 35, 37, 40, 45], it was hypothesized that larger knee internal/external rotation would induce larger sliding length on the lateral side. It was further hypothesized that knee rotation would not be correlated with either medial or lateral compartment sliding length but rather with the difference between them. The mechanism of how the rotational kinematics is related to the joint contact movement could contribute to the improvement of treatment for the post-traumatic osteoarthritis.

Materials and methods

Twenty-nine contralateral (uninjured) knees of ACL-reconstructed patients (33 ± 10 y.o.; 19 men, 10 women; height 175 ± 13 cm; weight 80 ± 16 kg; KT-1000 measurement at 89 N side-to-side difference (injured–uninjured) 1.2 ± 1.6 mm; selected from an ongoing Institutional Review Board-approved project) were retrospectively analyzed in this study. Inclusion criteria were patients who underwent unilateral primary ACL reconstruction and who were between the ages of 16 to 50. Exclusion criteria were any prior significant injury to the contralateral knee or any significant damage to the ACL reconstructed knee. Subjects underwent single bundle transtibial ACL reconstruction. During the surgical reconstruction, 1.6-mm tantalum spheres were implanted into the tibia and femur of each limb (3 per bone) for radiographic tracking. For both limbs, markers were inserted using a specially designed cannulated drill inserted through a small (5 mm) skin incision. After the surgery, patients started postoperative rehabilitation such as ROM and muscle strength exercise from day one and were allowed weight bearing as tolerated. Kinematic testing was performed after the subject completed his or her rehabilitation program and was cleared by the surgeon for return to light sports activities, between 5 and 9 months after ACL reconstruction surgery. Conventional kinematics and contact path data were determined using a previously described system combining dynamic stereo radiography (dynamic stereo X-ray or DSX) and computed tomography (CT) scans [1–3, 40–42]. A brief description of the measurement methods is provided below.

Dynamic stereo X-ray system for in vivo testing (Fig. 1)

Knee kinematics were determined using a dynamic stereo X-ray (DSX) system for acquiring high-speed stereo-radiographic images during an vivo, functional activity. Moderate-speed downhill running (2.5 m/s) was performed on a standard treadmill (Model L8, 46 × 152 cm belt, Landice Corp. Randolph, NJ, USA) with the rear supports elevated 25 cm to provide a 10° downward slope. Downward running was selected because it generates higher shear forces at the joint [26], resulting in greater shear motion. Downhill treadmill running is an unfamiliar and somewhat awkward activity for many individuals, and the transition speed between walking and running (2.3 m/s for level ground [28]) is lower for downhill locomotion [29]. A moderately slow running speed of 2.5 m/s was selected to insure that all subjects would be above the walk-to-run transition speed, while avoiding taxing any of the subjects beyond their abilities. For each trial, DSX images were acquired at a rate of 180 frames/s using a 90-kVp, 100-mA, 1-ms pulsed protocol, from shortly before footstrike through mid-stance for 1 step of the test leg (approximately 0.5 s duration). The DSX system consisted of two gantries (each containing a 100 kW radiography source, 30 cm image intensifier and 180 frame/s digital video system), configured to provide two beams parallel to the ground with an interbeam angle of 60°.

Knee kinematics measurement

Knee kinematics were assessed with dynamic radio-stereophotogrammetric analysis, a technique for determining three-dimensional kinematic information from stereo-pair radiographic images of musculoskeletal tissue with implanted high-contrast markers. This system is capable of tracking implanted markers with accuracy of approximately ±0.1 mm, as previously described [40]. Rotations

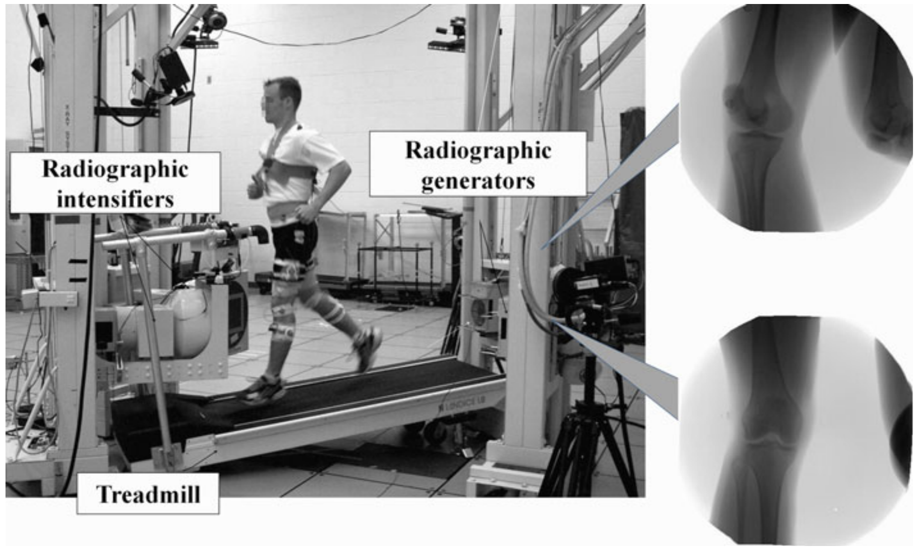

Fig. 1 Dynamic stereo X-ray (DSX) system (Henry Ford Health System, Detroit, MI). Two sets of radiographic generators, image intensifiers and high-speed digital video cameras simultaneously acquire dynamic radiographic images during downhill running (10° decline)

of the tibia relative to the femur were calculated using body-fixed axes (in the order flexion/extension, adduction/abduction and internal/external rotation) corresponding to the rotational component of the Joint Coordinate System originally described by Grood and Suntay [16]. Transformations between implanted marker-based coordinates and anatomical axes/landmarks were determined from CT, as previously described [40].

Joint contact path measurement

Tibia and femur CT scans were reconstructed into three-dimensional wireframe mesh bone models consisting of triangular elements. Location of the joint contact point was estimated using the distance-weighted centroid of the region of closest proximity between the surfaces of the femur and the tibia at each time-frame [1, 2]. Joint contact points for the nth frame were described for the tibia (x_n, y_n, z_n), using a Cartesian coordinate system aligned with the tibial plateau and for the femur (I_n, R_n, J_n) using a cylindrical coordinate system fitted to the distal femoral condyles (Fig. 2).

The contact path length was estimated in the sagittal plane, excluding medial–lateral translation (which was small relative to motion in the sagittal plane). The contact path excursions on the femur and the tibia were calculated during early stance (0–0.1 s after footstrike), by sequentially summing the sagittal plane distance between the joint contact points at consecutive frames (Eqs. 1, 2).

Femoral contact path

$$= \sum \sqrt{R_n^2 + R_{n+1}^2 - R_n R_{n+1} \cos(J_{n+1} - J_n)^2} \quad (1)$$

$$\text{Tibial contact path} = \sum \sqrt{(y_{n+1} - y_n)^2 + (z_{n+1} - z_n)^2} \quad (2)$$

The sliding length was estimated to assess shear motions between the femoral and tibial joint surfaces. For a pure rolling motion, the relative velocity of the contact points on the femur and tibia is zero, and the contact paths would

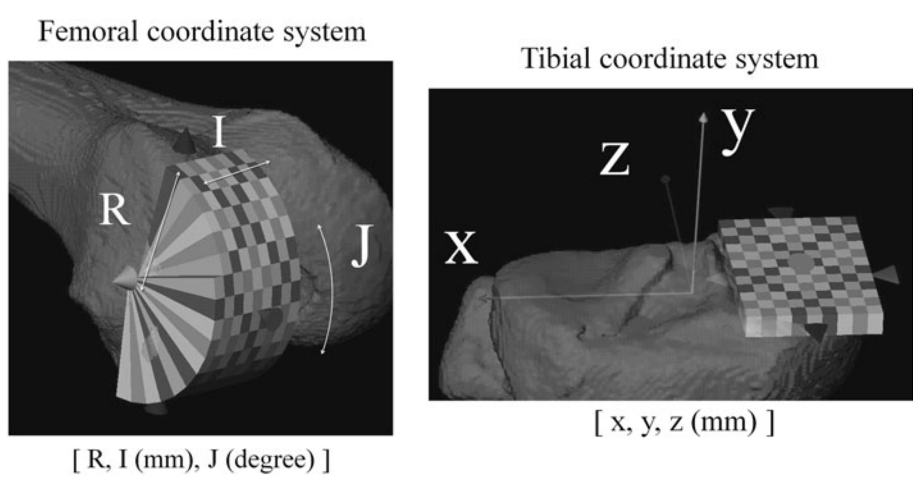

Fig. 2 Femoral and tibial coordinate systems. The medial and lateral femoral condyles are defined using a cylindrical coordinate system with long axis parallel to a line connecting the condyle centers. The tibial plateaus are defined in a rectangular coordinate system with the X–Z plane parallel to the articulating surface

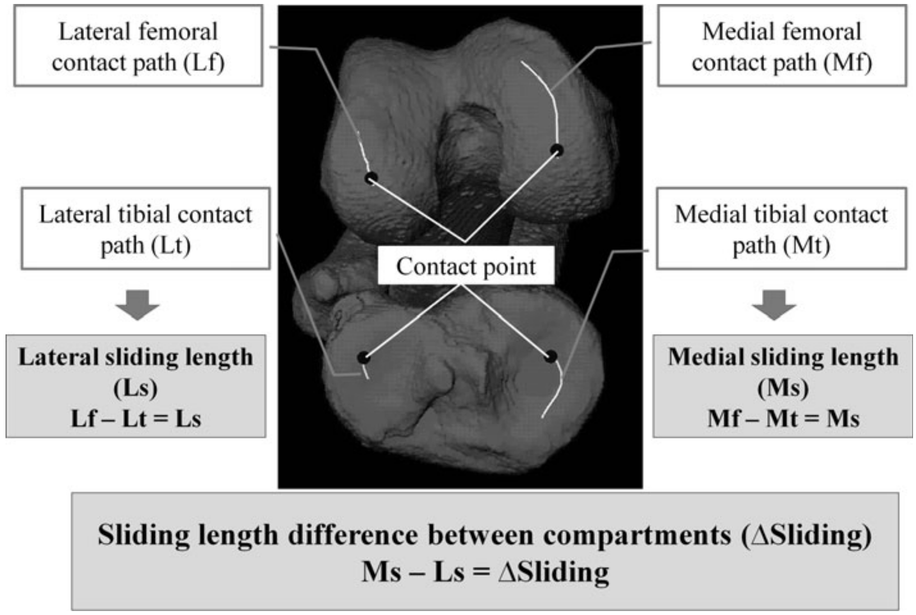

Fig. 3 Dynamic joint contact point and path length. Sliding lengths are calculated for both compartments, and the medial-lateral difference is determined

have equal length. Thus, the differences between the lengths of the tibial and femoral paths in the medial and lateral compartments are representative of the amount of sliding that occurred during each compartment during the joint motion. The difference in sliding lengths between medial and lateral compartments was also computed, as described in Fig. 3.

Statistical analysis

Sliding lengths in the medial and lateral compartments were compared using a paired *T* test. Correlations between knee internal/external rotation and the 3 sliding measures (medial slide length, lateral slide length and medial-lateral slide length difference) were determined by Pearson's correlations and stepwise multiple regression analysis. The statistical significance was set at *P* value less than 0.05. All statistical calculations were performed using PASW Statistics 18 (formerly SPSS Statistics, IBM Corp., Armonk, NY).

Results

All the knees were internally rotated during the early- to mid-stance phase of running (0–0.1 s after foot strike) by an average of 9.7° ± 3.5° (Fig. 4), with average knee flexion of 26.8° ± 6.7°. As shown in Fig. 5, the femur rolled on the tibial plateau after foot strike, shifting the femoral contact point posteriorly. The tibial contact point also shifted posteriorly during early stance. Mean contact path length on the medial femoral condyle was significantly larger than that on the lateral femoral condyle ($P < 0.05$). Tibial contact path on the medial and lateral

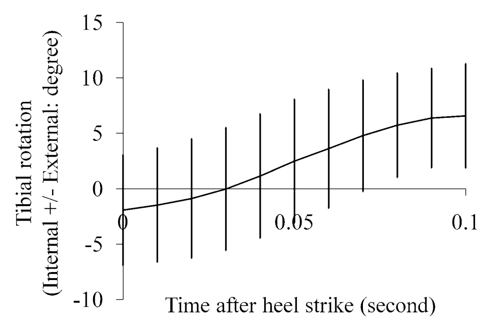

Fig. 4 Mean tibial axial rotation (0.01 s intervals) during mid-stance phase of running (0–0.1 s after foot strike) (average ± SD)

sides was similar (NS). The sliding length on the medial side was significantly larger than that on the lateral side ($P < 0.05$; Table 1).

Knee internal rotation correlated most strongly with the difference in sliding length between compartments ($P < 0.01$, $R = 0.85$). Lateral sliding length was weakly correlated ($P < 0.05$, $R = -0.40$) with knee internal rotation (Figs. 6, 7). The relationship between medial sliding length and knee internal rotation was not statistically significant ($R = 0.26$; NS). Multiple regression analysis demonstrated that the difference in the sliding length between medial and lateral compartments was the only predictor for knee internal rotation; adding compartmental sliding lengths did not improve the predictive value.

Discussion

The most important finding of the present study was that larger tibial internal rotation was associated with more sliding motion in the medial compartment during running

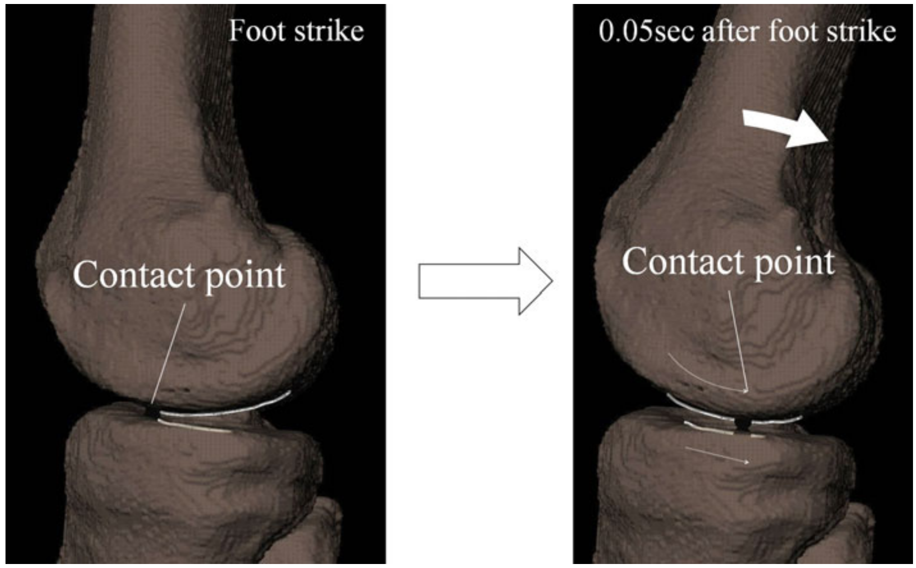

Fig. 5 Contact point movement. As knee flexion increased after foot strike, both femoral and tibial contact points (indicated by *black dots*) moved posteriorly

Table 1 Contact path length for each compartment (medial or lateral) on each bone (febur and tibia) (mean ± SD)

	Medial (mm)	Lateral (mm)
Femoral contact path	20.8 ± 6.4*	13.0 ± 4.6
Tibial contact path	10.6 ± 4.5	10.7 ± 3.6
Sliding length (difference on contact path)	10.2 ± 3.8*	2.3 ± 4.0

* Significantly larger than lateral side, $P < 0.05$

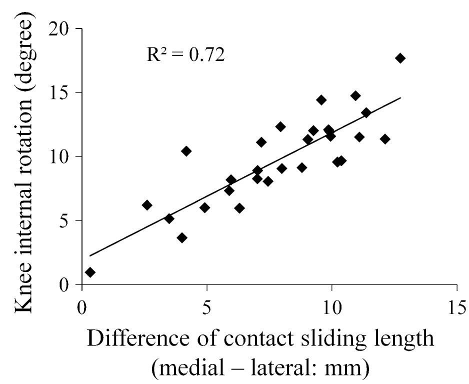

Fig. 7 Knee axial rotation and sliding length difference were highly correlated ($R^2 = 0.72$, $P < 0.01$)

	Knee internal rotation	Medial sliding length	Lateral sliding length	Difference of sliding length between compartments
Knee internal rotation				
Medial sliding length	0.26			
Lateral sliding length	-0.40*	0.70**		
Difference of sliding length between compartments	0.85**	0.32	-0.46*	

Fig. 6 Pearson's correlation matrix for knee internal rotation, medial and lateral sliding lengths and the difference in the sliding length between compartments. *$P < 0.05$; **$P < 0.01$

activity. It was hypothesized that larger knee rotation would induce larger sliding length on the lateral side, based on the medial pivot theory which suggests that, during flexion and transverse-plane rotation, the lateral tibial joint contact point moves further than the medial contact point [6, 11, 12, 18, 19, 21, 34]. The data provided here fail to support this hypothesis, as longer contact sliding lengths were observed on the medial side. The second hypothesis, that knee rotation would be correlated with the difference between knee sliding lengths in the medial and lateral compartments, was supported as the knee rotation, and the difference in the sliding length between compartments was closely related.

The relationship between knee joint kinematics and joint contact mechanics can be more clearly understood by examining both the tibial and femoral sides of the articulating surfaces (rather than the tibial side only, as has been typical for previous studies). The tibial joint contact point movement is composed of a combination of rolling and sliding movement [19]. As the knee flexes, rolling movement shifts the femur posteriorly on the tibia, whereas sliding movement translates the femur anteriorly. The balance of both movements sits the femur in a proper articulating location on the tibia. In this study, the sliding length, i.e., the femoral anterior shift relative to the tibia in the compartment, was longer in the medial side, resulting in external rotation of the femur relative to the tibia. Both articulating joint surfaces should be simultaneously examined for proper understanding of the joint contact condition and further relationship with the knee kinematics.

The current results support that lateral pivot movement (i.e., with the rotational axis located on the lateral side of knee joint) occurs during running, but this may not necessarily apply to all in vivo activities. Similar lateral pivot movement has been observed during normal walking [22, 24] and active weight-bearing knee extension [20]. Though other studies have reported greater contact point translation in the lateral compartment associated with tibial internal rotation during knee flexion (providing the basis for the medial pivot movement concept) [6, 11, 12, 18, 19, 21, 34], these experiments were conducted either using cadavers or under loads much lower than encountered during most functional activities. While the location of the knee rotational axis may be dependent on the specific loading condition, during functional locomotion (walking and running), it is positioned primarily on the lateral side of the joint. Thus, since current total knee arthroplasty implants were designed to duplicate the medial pivot movement [8, 30, 35, 44], they may not restore natural motion during demanding activities.

Residual rotational instability after ACL injury remains even after conventional ACL reconstruction [14, 15, 32, 33, 41, 42]. However, the effects of abnormal knee kinematics on joint contact and the resulting implications for the development of knee osteoarthritis have yet to be fully characterized. Stergiou et al. [39] proposed a theoretical perspective for the development of osteoarthritis in both ACL-deficient and reconstructed knees, such as abnormal shifts of joint loading to normally unloaded regions [39]. The data presented here could suggest a possible mechanism consistent with Stergiou's theory, that greater sliding in the medial compartment associated with increased tibial rotation creates abnormal knee loading that may contribute to initiation and progression of osteoarthritis.

There are several limitations in this study. First, the tested subjects were contralateral knees in ACL-reconstructed patients. Although the kinematics of contralateral knees in ACL-reconstructed patients are similar to the normal control during flexion-extension or lunge [25, 34, 38], contralateral knee kinematics in ACL-reconstructed patients might be different from the intact knees of healthy subjects, especially during a high-demand activity such as downhill running. Second, it was estimated the sliding length by a simple comparison and subtraction between tibial and femoral contact paths on the sagittal plane. The ratio between rolling and sliding movement varied across subjects due to differences in joint geometry (i.e., the angle of tibial slope and joint congruity). This calculation can only approximate total joint contact sliding length and cannot fully discriminate between rolling and sliding movement. The instantaneous contact point velocity might provide a more specific assessment of rolling versus sliding [1], but is more sensitive to errors in kinematics and joint surface geometry. Sliding length measured over a fixed time (as was done for this study) represents average contact velocity, and this relatively simple and robust comparison and subtraction of contact paths is thought to be meaningful from a clinical perspective. In addition, subjects were tested only during running. As mentioned before, knee kinematics are highly activity dependent. Because running places the joint under significant stress (with peak forces up to 10–14 times of body weight [36]), it enables evaluation of knee behavior closer to the extremes of its functional envelope. However, future studies should also consider other more frequent but lower-intensity functional activities, such as walking and stair climbing.

The result of this study could contribute to the knowledge about the impact of the knee rotational kinematics on joint contact condition, and the clinical interpretation was that rotational kinematics abnormality should be treated for restoring normal balance of joint sliding between medial and lateral compartments and preventing future osteoarthritis.

Conclusions

During a demanding functional activity (downhill running), greater tibial internal rotation was associated with larger magnitude of sliding motion in the medial compartment. A significant relationship was also identified between knee rotational kinematics and the balance between medial and lateral joint contact condition.

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