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Kinematics and Arthrokinematics in the Chronic ACL-Deficient Knee are Altered Even in the Absence of Instability Symptoms

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Abstract

Purpose—To analyze the *in vivo* kinematics and arthrokinematics of chronic ACL-deficient (ACL-D) and unaffected contralateral knees during level walking and downhill running using dynamic biplane radiography. It was hypothesized that ACL-D knees would demonstrate increased anterior translation and internal rotation, and that ACL-deficiency would alter the tibiofemoral contact paths in comparison to the unaffected contralateral side.

Methods—Eight participants with unilateral chronic ACL-D without instability symptoms were recruited. The contralateral unaffected knee was considered as control. Kellgren-Lawrence (K-L) grades were determined from ACL-D and unaffected knees. Dynamic knee motion was determined from footstrike through the early stance phase (20%–25% of gait cycle) using a validated volumetric model-based tracking process that matched subject-specific CT bone models to dynamic biplane radiographs. Participants performed level walking at 1.2 m/s and downhill running at 2.5 m/s while biplane radiographs were collected at 100 and 150 images per second, respectively. Tibiofemoral kinematics and arthrokinematics (the path of the closest contact point between articulating subchondral bone surfaces) were determined and compared between ACL-D and unaffected knees. A two-way repeated measures analysis of variance was used to identify differences between ACL-D and unaffected knees at 5% increments of the gait cycle.

Results—Anterior-posterior translations were significantly larger in ACL-D than unaffected knees during level walking (all $p < 0.001$) and downhill running (all $p \leq 0.022$). Internal rotation showed no significant difference between ACL-D and unaffected knees during level walking and downhill running. Closest contact points on the femur in ACL-D knees were consistently more anterior in the lateral compartment during downhill running (significant from 10% to 20% of the

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Authors' contributions CY performed data processing and analysis, and drafted the manuscript. YT assisted in data analysis and revised the manuscript. AL revised the manuscript and provided clinical interpretation of the results. FF contributed to drafting and revision of the manuscript and provided clinical interpretation of the results. WA contributed to data processing and data analysis, drafting and revision of the manuscript, and biomechanical interpretation of the results.

Conflict of interest The authors declare that they have no conflict of interest.

gait cycle, all $p \leq 0.044$), but not during level walking. No differences in medial compartment contact paths were identified. Half of the participants had asymmetric KL grades, with all having worse knee OA in the involved knee. Only 2 relatively young individuals had not progressed beyond stage 1 in either knee.

Conclusion—The results suggest that anterior translation and knee joint contact paths are altered in ACL-D knees even in the absence of instability symptoms. The clinical relevance is that ACL-D patients who do not report symptoms of instability likely still demonstrate altered knee kinematics and arthrokinematics compared to their uninvolved limb.

Keywords

Anterior cruciate ligament; kinematics; arthrokinematics; In vivo; biplane radiography

Introduction

The primary function of the anterior cruciate ligament (ACL) is to stabilize translation and rotation of the tibia relative to the femur [2, 10]. ACL injury alters knee kinematics and can lead to early onset of osteoarthritis (OA) [6, 22, 29]. While ACL reconstruction is considered to be the first choice in ACL injured patients with symptoms of instability[24, 33], some patients cope with the ACL-deficiency and return to sports and daily activities [16, 17, 27] without symptoms of instability.

There have been many studies analyzing the *in vivo* kinematics of ACL-D knees [5, 9, 12, 13, 32, 35, 39, 42, 43]. These previous reports of knee kinematics comparing ACL-D and control knees are inconsistent when describing differences in internal/external rotation, or in anterior/posterior translation. One reason for these varying results may be that most of these previous *in vivo* studies tracked knee motion using skin-mounted markers, which are known to be affected by skin-motion artifact (*i.e.* motion between the skin and underlying bone). Errors due to skin motion artifact can average up to 6.4° in rotation and 7.1 mm in translation during running, making this technique inappropriate for assessing joint arthrokinematics (*i.e.* the relative motion between articulating joint surfaces) [21]. More recently, biplane radiography or fluoroscopy has been used to provide sub-millimeter accuracy in tracking *in vivo* tibiofemoral motion [7, 8, 25, 26, 41]. However, most previous reports using biplane radiography were limited to large range of motion, slow-speed, and low-impact activities such as a quasi-static lunges or squatting [7, 25, 41]. Depending on the task analyzed, tibiofemoral contact point in ACL-D knees were more posterior in both the medial and lateral compartments[25], or more posterior only in the medial compartment [20], or more posterior in the medial compartment and more anterior in the lateral compartment [8]. Due to the importance of the ACL in high impact dynamic activities, it may be more appropriate to analyze kinematics of ACL-deficient knees during dynamic weight-bearing activities in ranges of knee motion closer to extension where the ACL plays a greater role in stability. [19, 38]. Importantly, previous biplane fluoroscopic studies of ACL-D knees studied pre-surgical patients who reported instability after ACL-injury, rather than chronic ACL-D knees with no reports of instability. It is currently unknown how well the kinematics and arthrokinematics match between chronic ACL-D knees without instability symptoms and unaffected contralateral knees during dynamic functional activities.

The purpose of this study was to analyze the *in vivo* kinematics and arthrokinematics of chronic ACL-D and unaffected contralateral knees during level walking and downhill running using dynamic biplane radiography. It was hypothesized that ACL-D knees would demonstrate greater anterior translation and internal rotation, and that ACL-deficiency would alter the tibiofemoral contact points in comparison to the unaffected contralateral side.

Materials and Methods

A total of eight participants with chronic ACL-D were enrolled. There were 4 males and 4 females with a mean age of 42 ± 16 years. Mean duration from ACL injury to testing was 67 months (range 8 to 264 months). The average body mass index (BMI) was 24 ± 3.6. Participants were drawn from a sample of people known to the authors as chronic ACL-D subjects with no symptoms of instability who were able to participate in daily activities and some sports without symptoms of instability. Participants were diagnosed as ACL-deficient by an experienced orthopaedic surgeon from their history, findings of positive Lachman and pivot-shift test, and magnetic resonance images (MRIs). No other ligament injuries or meniscal tears requiring resection of more than one-third of the radial width of the meniscus were included. Inclusion criteria were no symptoms of knee instability, locking, or catching sensations, and no report of previous injury to the unaffected knee.

The knees of each subject were scanned by computed tomography (CT) (LightSpeed Pro 16, GE Medical Systems) from 15 cm proximal to 15 cm distal to the joint line with a slice interval of 0.625 mm. Three-dimensional (3D) bone models were created from the series of two-dimensional CT slices using Mimics software (Materialise, Leuven, Belgium). Anatomic coordinate systems were created in the right femur and right tibia of each participant. The bone models of the left side were mirror-imaged and co-registered to the right side bone models, and the anatomic coordinate systems were copied from the right to left side bone models. In this way, the anatomic coordinate systems were identical between the left and right sides within each participant [37].

Dynamic knee motion was examined during level walking at 1.2 m/s and downhill running at 2.5 m/s on an instrumented dual-belt treadmill (Bertec Inc, Columbus, Ohio, USA). Ground reaction forces recorded by the treadmill at 1000 Hz were used to determine gait cycle length and were analyzed to ensure that the participants were not favoring one leg over the other during walking and running. The treadmill provided a 10° downward slope during the downhill running test. The task of downhill running was included because it is relatively stressful on the ACL but can be performed in a controlled, repeatable fashion within the laboratory environment and is unlikely to put the individual at significant risk for injury [19].

Synchronized biplane radiographs were acquired at 100 Hz during walking and at 150 Hz during running, with 1.5 ms and 1.0 ms pulsed exposures, respectively, to limit motion blur, and X-ray generator settings of 90 kVp and 150 mA. Three successful trials of each activity were collected for the ACL-D and for the unaffected knee, resulting in a total of 12 trials per participant. All trials of the same activity and knee were averaged for each participant. Radiographic data were analyzed from footstrike (determined by the instrumented treadmill) to early-stance phase of gait/running. For the purpose of this study, the early-stance phase was defined as footstrike to 25% (walking) or 20% (running) of the gait cycle. Subject-specific CT-based bone models of the femur and tibia were matched to the biplane radiographs using an automated matching process that has been validated *in vivo* to have an accuracy of 0.7 mm or better in translation and 0.9 degrees or better in rotation [3](Figure 1). Coordinate systems constructed in the femur and tibia were used to calculate relative translations (anterior-posterior, medial-lateral, and proximal-distal) and rotations (flexion-extension, internal-external, and abduction-adduction) at the knee joint following the methods described by Grood and Suntay [14]. In addition, the path of the center of closest contact between subchondral bone surfaces in each compartment of the femur and tibia was determined using the distance-weighted centroid of the closest region between tibiofemoral subchondral bone surfaces [23]. The migrations of medial and lateral compartment center of closest contact points were calculated in the anteroposterior (AP) and mediolateral (ML) directions from footstrike to early-stance phase (Figure 2). This study was approved by the University of Pittsburgh Institutional Review Board (PRO08030126) and all participants provided informed written consent to participate in this study.

Statistical Analysis

A 2-way repeated measures analysis of variance test (leg by gait cycle) was used to compare anterior-posterior translation, internal-external rotation, and contact point location between ACL-D knees and unaffected knees at each 5% interval of the gait cycle from footstrike to early stance. SPSS 24.0 (SPSS GLM3, SPSS Inc, Chicago, IL, USA) was used for the statistical analysis, with significance set at $p < 0.05$. Using the sample size of 8 participants, 80% power, and a correlation between repeated measurements of 0.8, the study was powered to detect an effect size η^2=0.12, which is between a medium (η^2=0.06) to large (η2=0.14) effect.

Results

Anterior translation of the tibia (ATT) was significantly larger in ACL-D knees than unaffected knees at each 5% interval of the gait cycle from footstrike to early stance during level walking (all $p \leq 0.001$) (Figure 3a). During downhill running, ATT was also significantly larger in ACL-D knees from footstrike through early stance (all $p \leq 0.022$) (Figure 3b). On average, internal rotation of the tibia was greater in ACL-D knees, however, these differences were not significant during walking (n.s.) and running (n.s.) (Figure 3c and 3d).

No differences in peak ground reaction forces were observed (n.s.) between ACL-D knees and unaffected knees during level walking or during downhill running. During level walking, the peak ground reaction force was 840.0 ± 253.3 N at 15% of the gait cycle in ACL-D knees and was 814.2 ± 319.5 N at 15 % of the gait cycle in unaffected knees (Figure 4a).

During downhill running, the peak ground reaction force was 1442.0 ± 169.6 N at 15% of the gait cycle in ACL-D knees and was 1447.0 ± 339.9 N at 10% of the gait cycle in unaffected knees (Figure 4b).

During level walking, no differences between knees were found in AP contact point location on the medial or lateral femoral condyle (Figure 5a and 5b). During downhill running, no differences between knees were found in anterior-posterior contact point location on the medial femoral condyle. In contrast, during downhill running, lateral femur contact points were significantly more anterior in ACL-D knees from 10% to 20% of the gait cycle (p = 0.020, 0.044, and 0.007 respectively). (Figure 5c and 5d).

All K-L grades were 2 or lower. Fifty percent of the participants had asymmetric K-L grades, with all of these participants having worse knee OA in the involved knee. Only 2 very young individuals had not progressed beyond stage 1 in either knee.

Discussion

The most important finding of the present study was that in participants with chronic ACL-D without symptoms of instability, anterior translation of the tibia (ATT) was significantly larger during level walking and downhill running compared to the unaffected contralateral knee. Additionally, tibiofemoral contact points were more anterior on the lateral femoral condyle in the ACL-D knee during the early support phase of downhill running.

In vivo kinematics of the tibiofemoral joints in ACL-D knees in our study were similar to those reported by previous studies on ACL-D knees [5, 25, 42]. Resisting ATT is one of the main functions of the ACL [2], and increased ATT has been reported at heel strike [5], stance phase of walking [42], and full extension to mild flexion during loading [25] in ACL-D knees, and these were consistent with our study. Previous studies using a 2D/3D registration technique to assess weight-bearing knee flexion reported that contact points on the tibia migrated more posterior in ACL-D knees from full extension to mild knee flexion [20, 25], consistent with increased ATT in ACL-D knees. Another study that analyzed weight-bearing knee flexion using a 2D/3D registration technique reported that tibial contact points were shifted about 3 mm posteriorly from full extension to 15° flexion in ACL-D knees, and the screw home movement [30] (*i.e.* external tibial rotation as the knee moves from flexion to terminal extension in the normal knee) had been lost [8]. Results in our study showed an anterior shift of the contact point on the lateral femoral condyle in ACL-D knees. This finding may suggest the loss of screw home movement [8, 30] and existence of the anterolateral rotatory instability (ALRI) reported in ACL-D knees [15, 28, 34, 36]. Results from internal rotation of the tibia showed a similar pattern to previous studies [7, 12], however, no differences between sides were observed. The failure to identify differences between ACL-D and unaffected knees in terms of internal rotation may be due to a number of factors, including small sample size or gait adaptation in chronic ACL-D knees [9]. Additionally, testing was limited to only straight-ahead movements that did not necessitate large rotation or pivoting movements that may have revealed differences between ACL-D and unaffected knees.

Some previous studies have reported no difference in ATT or rotation during walking or running in ACL-D knees [32, 39]. One reason for the disagreement between previous results and the present findings is that skin-mounted markers were previously used to estimate knee kinematics. Skin-mounted markers have been demonstrated to have poor accuracy when estimating tibiofemoral kinematics during dynamic movements (7.1 mm error in AP translation and 6.4° error in internal-external rotation) [21]. Another explanation for discrepancies between previous research and the current findings is participant characteristics. Previous studies have tested participants with acute or sub-acute ACL-injury who eventually underwent reconstruction, whereas the present study included only chronic ACL-D subjects who had no reports of symptomatic instability and who did not eventually have surgery. Therefore, these previous studies were generalizable only to a subgroup of patients who required ACL reconstruction due to persistent instability of the knee joint, while the present study was deliberately aimed at assessing chronic ACL-D individuals who did not require surgery. The present results indicate that side-to-side kinematic and arthrokinematic differences exist even in the patient group that reports no symptoms of instability.

As previous studies have demonstrated, the loss of normal ACL function is associated with an increased risk of meniscal or chondral injury [1, 4], and abnormal joint kinematics and arthrokinematics may cause early onset [6, 22] and progression of osteoarthritis [11, 18]. The current study suggests that individuals with ACL-D knees may be susceptible to arthritic changes associated with the abnormal joint kinematics and arthrokinematics even if they are coping with the ACL-deficiency and adapting without obvious instability symptoms.

In this small sample, 50% of participants had a poorer KL grade in the injured knee, and an additional 2 subjects had grade 2 changes in both knees. While no cause and effect relationships can be determined from these data, some interesting hypotheses can be offered. In this group of individuals who were tested at least 8 months and up to 22 years after injury, small but significant kinematic differences exist between limbs during both walking and running. It is possible that the small changes seen between limbs may cause greater degeneration in the ACL-D limb when compounded over time. Clearly, further work is needed to determine a causal effect and a much greater sample size would be needed to perform sub-group analysis based upon the degree of joint degeneration.

There are several limitations to this study. First, the small sample size may have precluded identifying some true differences. However, in spite of the small sample size, several significant differences were identified in this study, suggesting the measurement techniques and tested activities were sufficient to identify the largest kinematic and arthrokinematic changes that occur in chronic ACL-D patients. Second, in spite of the high variability in the age range and time post-injury of the participants, the results were consistent across participants, with no clear outliers influencing the results. Additional potential confounding variables that we were unable to assess include muscular strength and pain in the ACL-D and unaffected legs. Third, in order to minimize risk to the participants, no cutting or pivoting activities were tested. Testing these movements would clearly be valuable to challenge and assess the rotary stability of the ACL-D knee. Nonetheless, the contact path analysis still suggests that anterolateral rotatory instability may exist in the ACL-D knee even in straight-ahead walking and running. Fourth, the present analysis is limited to kinematics and arthrokinematics of the knee joint and does not encompass any estimate of articular cartilage tissue loading. Although the ground reaction force data indicate that external loading was not affected by ACL-D, an advanced and validated computational model would be necessary to confirm that there were also no differences between knees in terms of cartilage and meniscus loading. Finally, knee kinematics were analyzed only from footstrike through the early-stance phase of walking and running, limiting knee flexion to about 30°. However, the ACL is subjected to relatively higher tension when the knee is near full extension to mild flexion [31, 40], and therefore assessment of motion at these lower flexion angles, such as during the current analysis, is clinically relevant.

Conclusion

In vivo kinematics and arthrokinematics of ACL-D knees were analyzed using dynamic biplane radiography during level walking and downhill running. ATT was significantly larger and subchondral bone closest contact points were shifted more anterior on the lateral femoral condyle from footstrike to early stance in ACL-D knees. These results serve to alert clinicians and patients that chronic ACL-D knees, even in the absence of reported instability, appear to demonstrate subtle changes in tibiofemoral kinematics and arthrokinematics.

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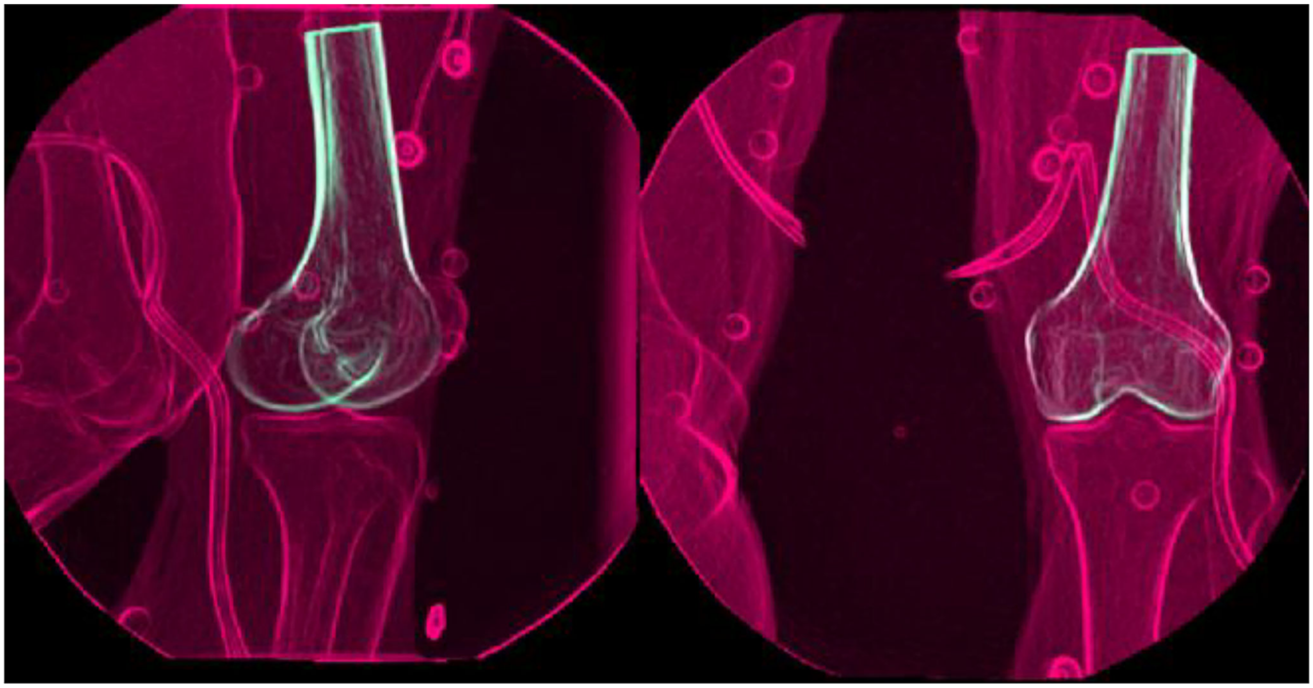

Fig. 1.
The model-based tracking process. Subject-specific CT-based bone models were matched to the biplane radiographs. Tracked motion of the femur and tibia bones was used to determine 3D kinematics of the tibiofemoral joint.

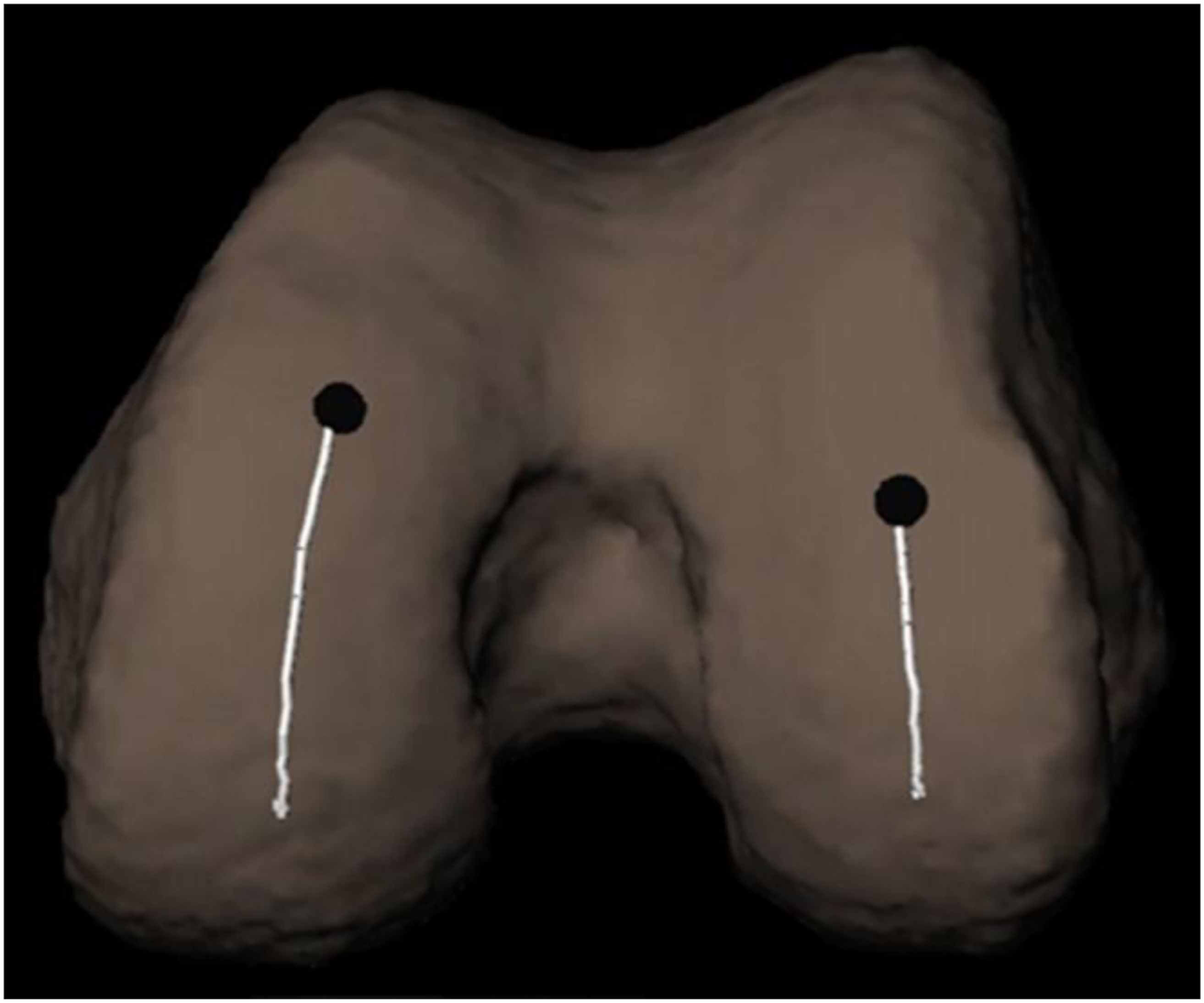

Fig. 2.

The center of closest subchondral bone contact point (black ball) and the migration of the closest contact point (white lines) on the medial and lateral femoral condyle.

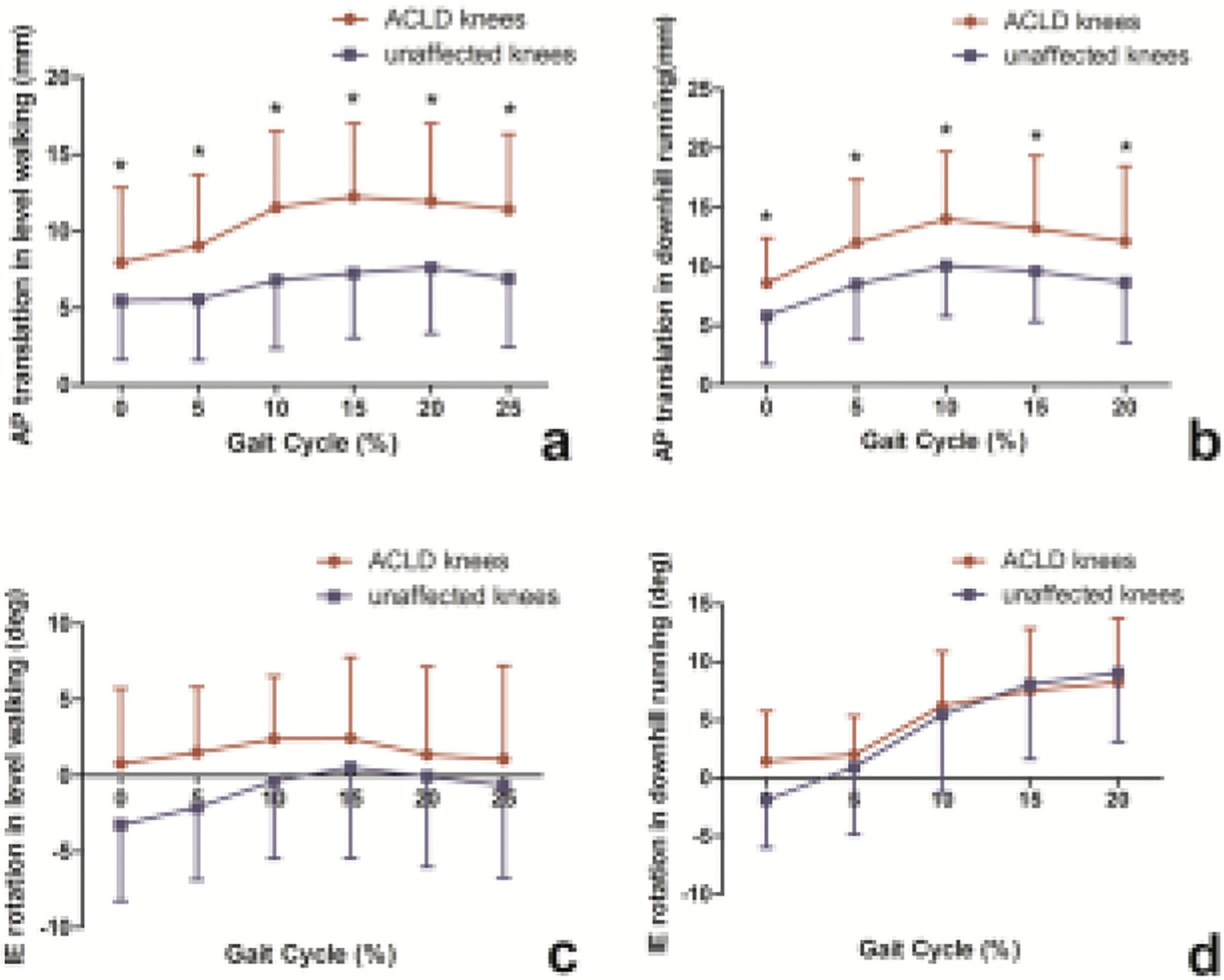

Fig. 3.

Tibiofemoral anterior-posterior (AP) translation and internal/external (IE) rotation during walking and running in unaffected and ACL-deficient (ACL-D) knees. AP translations were significantly larger in ACL-D knees than unaffected knees during (a) level walking and (b) downhill running (* = $p < 0.05$). No differences between ACL-D and unaffected knees were identified in IE rotation during (c) level walking and (d) downhill running (n.s.). Error bars indicate inter-subject standard deviation. However, statistical tests were performed within-subjects (ACL-D *vs*. unaffected knees).

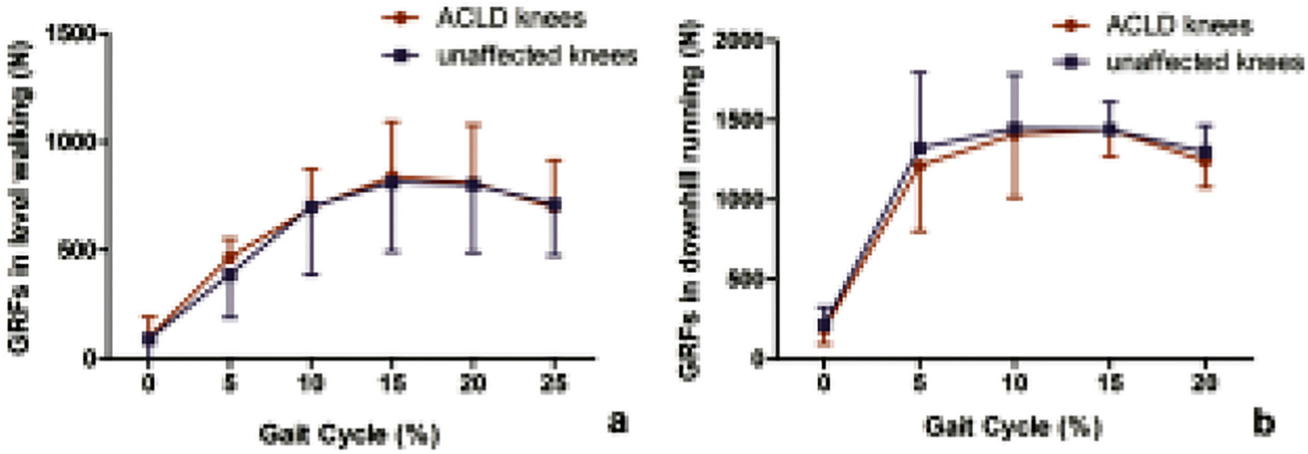

Fig. 4.

Ground reaction forces (GRFs) during (a) level walking and (b) downhill running. No significant differences between ACL-D and unaffected knees were identified.

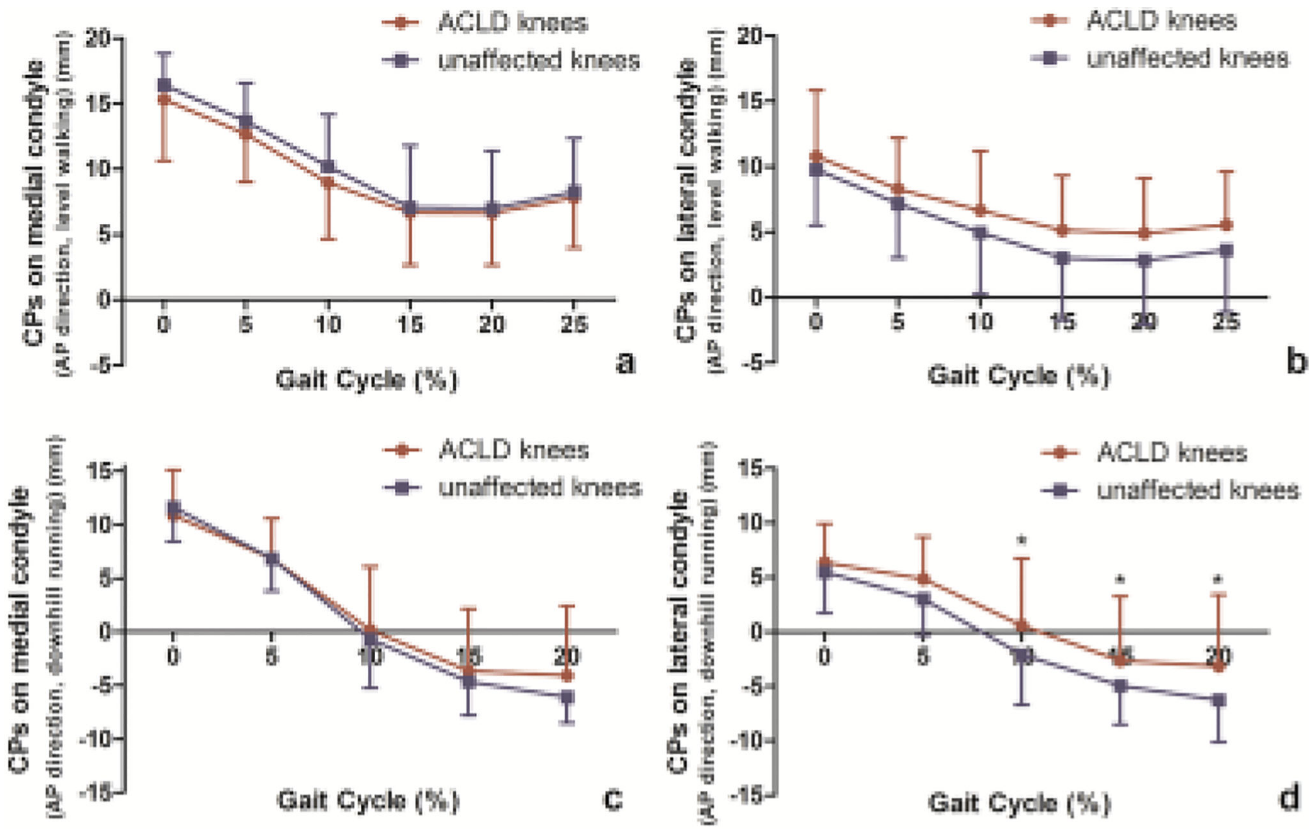

Fig. 5.

Contact points (CPs) location in the anterior-posterior direction on the medial and lateral condyle during walking and running. No significant differences between ACL-D and unaffected knees were identified in the medial condyle during walking (a) or running (c), as well as the lateral condyle during walking (b). Contact points were more anterior in the lateral femoral condyle at specific instants of the running (d) cycle (* = $p < 0.05$).