Original Research

Lower Limb Biomechanics During Level Walking After an Isolated Posterior Cruciate Ligament Rupture

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Background: The posterior cruciate ligament (PCL) is an important structure in knee stabilization. Knee cartilage degeneration after a PCL injury has been reported in several studies. Understanding the changes in movement patterns of patients with PCL ruptures could help clinicians make specific treatment protocols to restore patients' sporting ability and prevent joint degeneration. However, the kinematics and kinetics of the lower limb in patients with PCL injuries are still not clear.

Purpose: To investigate the biomechanical characteristics during level walking in patients with isolated PCL deficiency.

Study Design: Controlled laboratory study.

Methods: Three-dimensional videographic and force plate data were collected for 27 healthy male participants (control group) and 25 male patients with isolated PCL-deficiency (PCL-d group) walking at a constant self-selected speed. Paired and independent *t* tests were performed to determine the differences between the involved and uninvolved legs in the PCL-d group and between the PCL-d and control groups, respectively.

Results: Compared with the control leg, both legs in the PCL-d group had smaller knee moments of flexion and internal rotation; greater hip angles of flexion and adduction; greater hip moments of internal rotation; greater ankle angles of extension and adduction; and smaller ankle moments of flexion, adduction, and internal rotation. Moreover, compared with the uninvolved leg in the PCL-d group, the involved leg in the PCL-d group had significantly smaller knee extension angles and moments during the terminal stance phase, greater hip external rotation angles and extension moments, and smaller ankle adduction angles and flexion moments.

Conclusion: PCL ruptures altered walking patterns in both the involved and uninvolved legs, which could affect alignment of the lower limb and loading on the knee, hip, and ankle joints. Patients with PCL injuries adapted their hip and ankle to maintain knee stability.

Clinical Relevance: The kinematic and kinetic adaptations in the knee, hip, and ankle after a PCL rupture during level walking are likely to be a compensatory strategy for knee instability. The results of this study suggest that these adaptations should be considered in the treatment of patients with PCL ruptures.

Keywords: posterior cruciate ligament; gait; knee; hip; ankle; biomechanics

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A posterior cruciate ligament (PCL) rupture is a common knee injury. The incidence of PCL injuries varies from 3% to 44% of all knee injuries.[14,20,34] The PCL is twice as strong as the anterior cruciate ligament (ACL)[15] and is the primary restraint to posterior tibial translation.[4] In the case of treatment for isolated PCL injuries, the first choice is usually nonoperative treatment,[8,12,36] as nonoperative treatment can restore the patient to the same level of exercise as before the injury.[6,7,22,35] Compared with the results of ACL reconstruction, PCL reconstruction results are not satisfactory.[8,45]

However, 1 previous study[11] has reported knee cartilage degeneration after a PCL injury. During functional activity, patients with PCL injuries displayed significant knee instability. Radiographic examinations revealed that the rate of articular cartilage degeneration increased after a PCL injury.[2] Strobel et al[39] evaluated 82 patients with isolated PCL injuries by arthroscopic surgery and found that 57.3% of them suffered from articular cartilage lesions. Alterations in the kinematics and kinetics of the lower extremities could affect joint pressure distribution, which is a critical factor for joint degradation,[21,29,35] leading to degeneration of the tibiofemoral and patellofemoral joints.[30,37]

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Understanding the changes in movement patterns of patients with a PCL rupture could help clinicians build specific rehabilitation programs to restore patients' sports ability and prevent joint degeneration. However, few studies have focused on the knee kinematics or kinetics for patients with isolated PCL ruptures. The available analysis of weightbearing daily activities, such as walking, stair climbing, or squatting, is especially limited.[27] Even for walking, the most essential and routine daily activity, the influence of PCL deficiency remains unclear.[9,28,32,41] Some of these studies are in vitro studies,[23,25] while others[4,10,13,21,25,29] are in vivo, but both types only analyze static or quasistatic movements. Many issues related to lower limb biomechanics for patients with isolated PCL ruptures remain unclear and are worthy of further investigation.[12]

The purpose of this study was to investigate the biomechanical characteristics during walking in patients with isolated PCL deficiency. We hypothesized that (1) there would be significant differences in the kinematics and kinetics of the knee, hip, and ankle when compared among PCL-deficient involved legs, PCL-deficient uninvolved legs, and control legs during the stance phase of level walking and (2) patients with PCL deficiency would make adjustments to their hip and ankle biomechanics to prevent knee joint instability.

METHODS

Participants

A total of 25 male patients with complete isolated PCL ruptures (PCL-d group) scheduled for surgery and 27 healthy male participants (control group) volunteered to participate in this study. There were no significant differences in age or body mass index between the PCL-d and control groups (Table 1). There were 12 patients who had PCL ruptures on the right side and 13 patients on the left side; 16 patients in the PCL-d group had sports-related injuries, and 9 patients had nonsports-related injuries. All patients in the PCL-d group were examined via magnetic resonance imaging, manual laxity examination, and range of motion testing by well-experienced senior orthopaedic surgeons. The examination results were also confirmed by arthroscopic surgery 1 day (range, 0-6 days) after the examination. The manual laxity examination includes checking for the existence of posterior sag signs and a posterior drawer test. All the patients had no pain or instability during walking. The PCL-d group was formed from patients who visited our hospital from June 14, 2014, to August 8, 2017. The inclusion criteria included an isolated PCL rupture of at least 3 months' duration. The exclusion criteria were (1) additional knee ligament or meniscal damage; (2) serious damage to the ipsilateral hip, ankle joint, or contralateral lower limb (ligament ruptures or bone fractures); (3) age >50 years (to avoid age-induced osteoarthritis interference); (4) any cartilage injury grade >2 according to the Outerbridge classification; and (5) Tegner score[18] <3. Written informed consent was obtained from all participants, and the institution's medical ethics committees approved the study.

TABLE 1
Patients' Age and BMI[a]

	Control Group	PCL-d Group	*P*
Age, y	29.7 ± 5.8	27.4 ± 7.5	.2125
BMI, kg/m^2	24.1 ± 3.2	24.1 ± 2.7	.9746

[a] Data are shown as mean ± SD. BMI, body mass index; PCL-d, posterior cruciate ligament deficient.

TABLE 2
Characteristics of PCL-d Group[a]

Kneelax arthrometer difference between both legs, mm	6.5 ± 1.5
Time from injury, mo	9.6 ± 5.4
IKDC score	74.9 ± 10.2
Tegner score	4.6 ± 1.6
Lysholm score	80.6 ± 10.4

[a] Data are shown as mean ± SD. IKDC, International Knee Documentation Committee; PCL-d, posterior cruciate ligament deficient.

Basic information including the Kneelax arthrometer (Monitored Rehab Systems) finding, the time from injury, the International Knee Documentation Committee (IKDC) score, the Tegner activity score, and the Lysholm knee score for all patients in the PCL-d group is shown in Table 2. The Kneelax arthrometer was used to check laxity of the knee, and the side-to-side difference in the PCL-d group was calculated under a force of 132 N by pushing the tibia back relative to the femur at a knee flexion angle of 90° (involved leg: 8.2 ± 1.9 mm; uninvolved leg: 1.9 ± 0.7 mm).

Experimental Protocol

Each participant was asked to wear a pair of black spandex shorts. Passive reflective markers were placed bilaterally

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Ethical approval for this study was obtained from the Peking University Third Hospital Medical Science Research Ethics Committee (study 328-02).

at the anterior superior iliac spine, posterior superior iliac spine, lateral thigh, anterior thigh, lateral femoral condyle, medial femoral condyle, lateral shank, anterior shank, lateral malleolus, medial malleolus, navicular, posterior calcaneus, medial point on the calcaneus, lateral point on the calcaneus, head of the first metatarsal, base of the first metatarsal, head of the second metatarsal, head of the fifth metatarsal, base of the fifth metatarsal, and hallux.

A static standing trial was performed by each participant. The participants stood naturally with their arms crossed in front of their chest. Their 2 feet were separated by a width equal to their shoulders. During this trial, the participants did not lift their heels above the ground, while their trunk was allowed to lean forward naturally.

After static standing trials, each participant was asked to walk barefoot from one end of the walkway to the other at a comfortable self-selected speed. The participants could practice several times to get familiar with the movements before testing.

Isokinetic strength testing of both knees was performed after the walking test. All strength tests were carried out with the participant in a seated position.

Data Collection

Three-dimensional (3D) trajectories of the reflective markers were collected using an 8-camera motion capture system (Vicon) at a sample rate of 100 Hz. Ground-reaction force (GRF) signals were collected using 2 embedded force plates (AMTI) at a sample rate of 1000 Hz. Each participant was asked to perform 5 successful trials. A successful trial was characterized as each foot stepping on the force plates at a self-selected speed. Strength data were collected using the Biodex System 3 Multi-Joint Testing and Rehabilitation System (Biodex) at a sample rate of 256 Hz. A total of 5 maximal isokinetic repetitions were collected through a 90° arc of flexion and extension at an angular velocity of 60 deg/s. The seated patient was instructed to exert maximal effort throughout these repetitions.

Data Reduction

The raw 3D trajectories of the reflective markers were filtered through a Butterworth low-pass digital filter at an estimated optional cutoff frequency of 10 Hz. Kinematic and kinetic variables were calculated using Visual3D software (C-Motion). The parameters were normalized as 101 discrete points corresponding to a 0% to 100% stance phase from initial contact to toe-off. Based on 5 gait events, (initial contact, opposite toe-off, heel rise, opposite initial contact, and toe-off), we divided the whole stance phase into loading response phase, midstance phase, terminal stance phase, and preswing phase. Joint moments were normalized to body weight and standing height. To compare our results with external moments in the literature, we converted the internal moment to external moment in this study. Therefore, the moment was expressed as the external moment. Results of the isokinetic strength tests (peak torque normalized to body weight) were compared between limbs within the PCL-d group.

Statistical Analysis

Data from the control group were used to randomly select 1 leg from each control participant as the control leg. Each discrete kinematic and kinetic point was compared among the control leg group, the involved leg of the PCL-d group, and the uninvolved leg of the PCL-d group. Paired *t* tests were performed to compare kinematic parameters, kinetic parameters, and isokinetic results between the involved and uninvolved legs of the PCL-d group. Independent *t* tests were performed to compare kinematic and kinetic parameters between the involved leg of the PCL-d group and the control legs and between the uninvolved leg of the PCL-d group and the control legs. All statistical analyses were performed using the Matlab computer program package version 2016b (MathWorks). Statistical significance was defined as a type I error ≤ 0.05.

RESULTS

The walking speed of the PCL-d group (1.26 ± 0.12 m/s) was not significantly different from that of the control group (1.28 ± 0.11 m/s) ($P = .3820$). Both the peak isokinetic knee extension moment and peak isokinetic knee flexion moment at 60 deg/s for the involved leg of the PCL-d group (1.3 ± 0.4 and 0.6 ± 0.3 N·m/kg, respectively) were significantly smaller than those of the uninvolved leg of the PCL-d group (1.7 ± 0.5 and 0.8 ± 0.2 N·m/kg, respectively) ($P < .001$ and $P < .001$, respectively).

Kinematics and Kinetics of the Knee

Knee extension angles and moments were significantly smaller in the involved leg of the PCL-d group than those of the uninvolved leg of the PCL-d group during the terminal stance phase (Figure 1, A and B). No significant differences were found in knee abduction/adduction angles when compared with the involved leg of the PCL-d group, the uninvolved leg of the PCL-d group, and the control leg (Figure 1C). Knee adduction moments were significantly smaller in the uninvolved leg of the PCL-d group than those of the control leg during the loading response phase (Figure 1D). Knee external rotation angles were significantly greater in the uninvolved leg of the PCL-d group than those of the control leg during the preswing phase (Figure 1E). Peak knee extension moments during the terminal stance phase were 0.11 ± 0.08 for the involved leg of the PCL-d group and 0.15 ± 0.08 N·m/kg·m for the uninvolved leg of the PCL-d group ($P = .80$). Knee internal rotation moments were significantly smaller in the involved and uninvolved legs of the PCL-d group than those in the control leg during the late preswing phase (Figure 1F).

Kinematics and Kinetics of the Hip

Hip flexion angles were significantly larger in both legs of the PCL-d group than in the control legs during almost the entire stance phase (Figure 2A). The involved leg of the PCL-d group had significantly greater hip extension moments compared with the uninvolved leg of the PCL-d

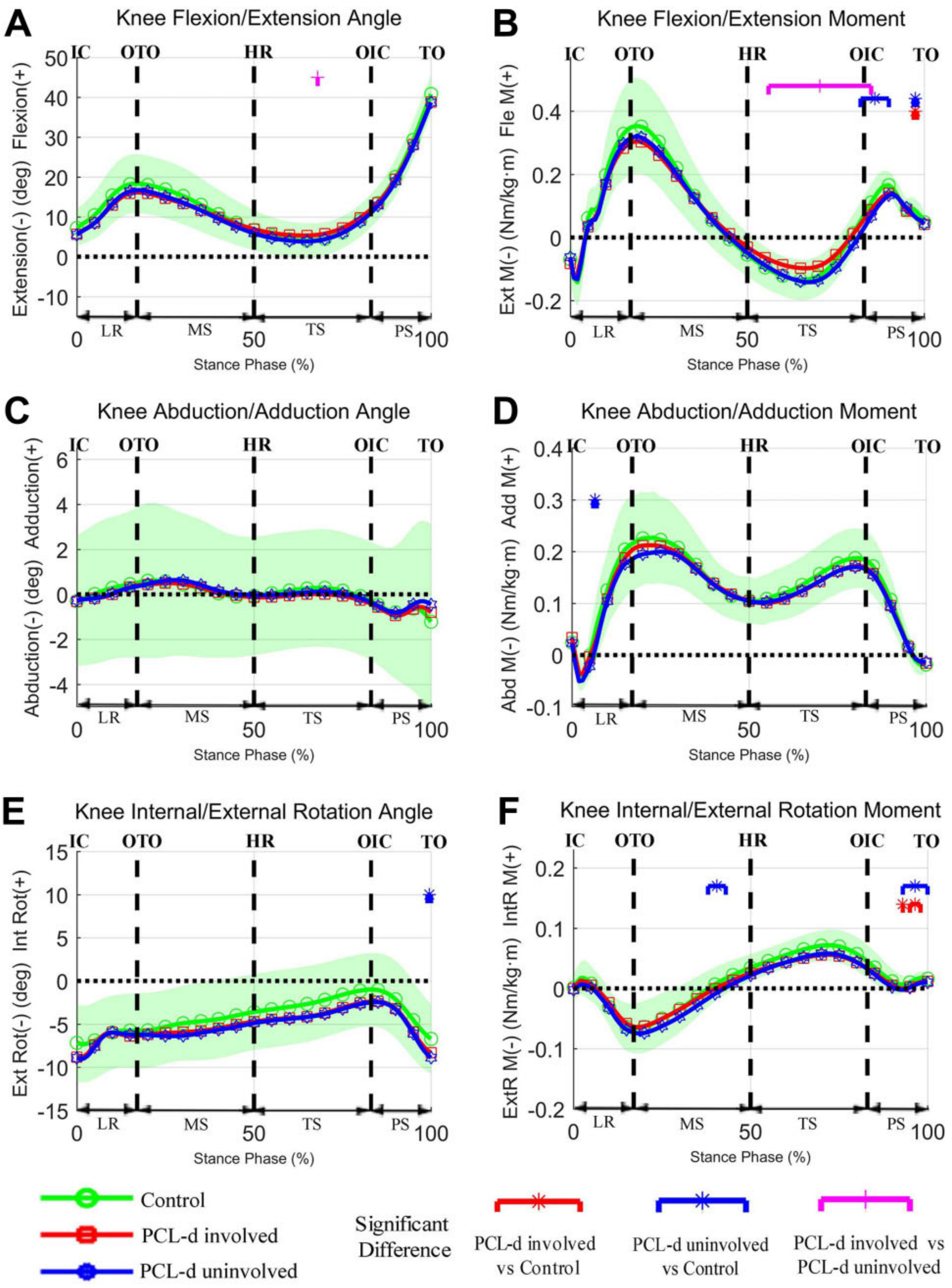

Figure 1. (A-F) The ensemble average of knee angles and moments during the walking stance phase. The green shaded areas are the knee angles and moments (mean ± SD) of the 27 control legs. Significant differences are marked with asterisks: $P < .05$. HR, heel rise; IC, initial contact; LR, loading response phase; MS, midstance phase; OIC, opposite initial contact; OTO, opposite toe-off; PS, preswing phase; TO, toe-off; TS, terminal stance phase.

group during the terminal stance phase, and the uninvolved leg of the PCL-d group had significantly smaller extension moments compared with the control legs during the terminal stance and preswing phases (Figure 2B). Significantly larger hip adduction angles were found in the involved leg of the PCL-d group compared with the control legs during the midstance phase, terminal stance phase, and preswing phase. This was also true for the uninvolved

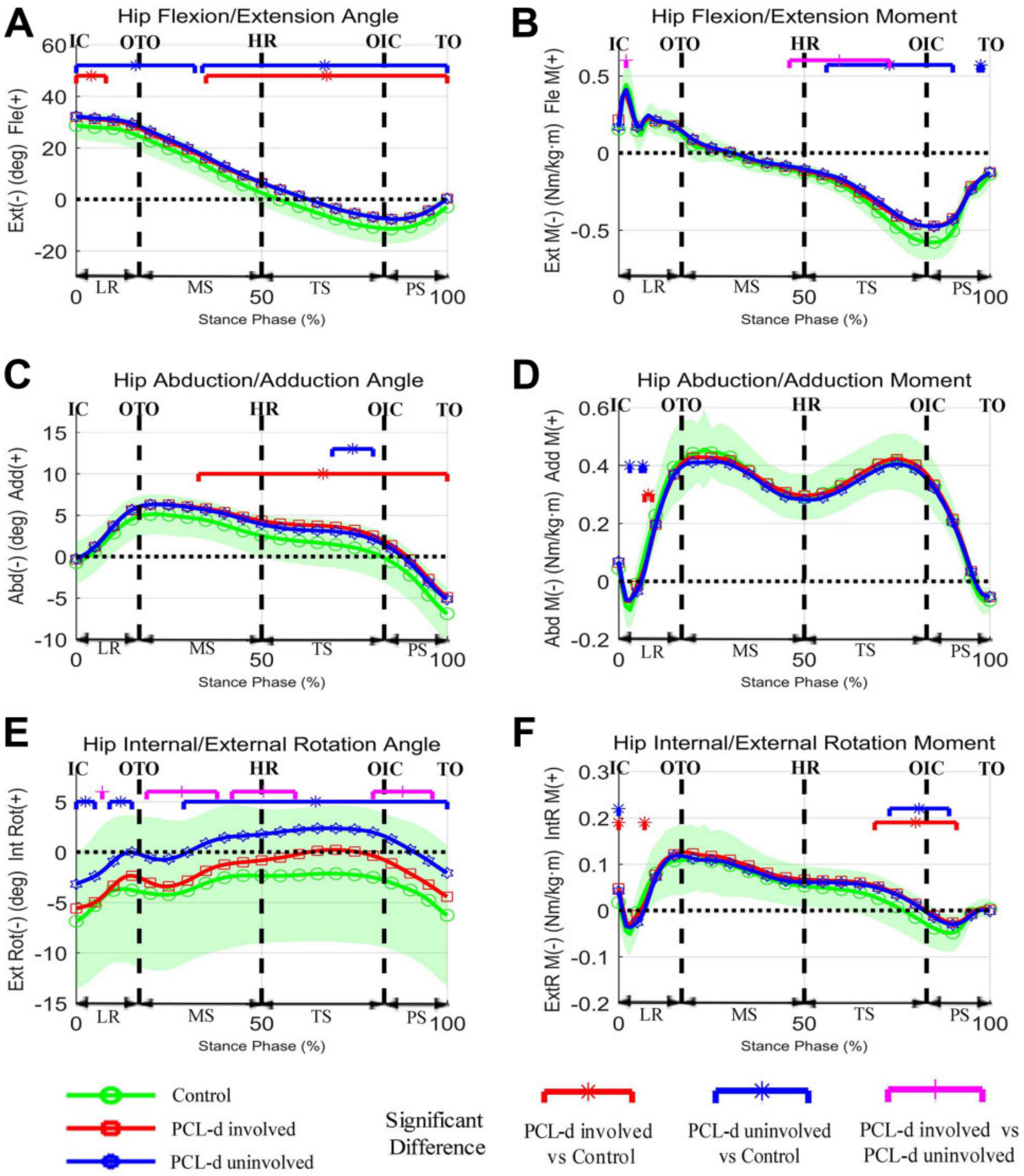

Figure 2. (A-F) The ensemble average of hip angles and moments during the walking stance phase. The green shaded areas are the hip angles and moments (mean ± SD) of the 27 control legs. Significant differences are marked with asterisks: $P < .05$. HR, heel rise; IC, initial contact; LR, loading response phase; MS, midstance phase; OIC, opposite initial contact; OTO, opposite toe-off; PS, preswing phase; TO, toe-off; TS, terminal stance phase.

leg of the PCL-d group during the terminal stance phase (Figure 2C). During the loading response phase, hip abduction moments were significantly smaller in the uninvolved leg of the PCL-d group than those of the control leg, and hip adduction moments were significantly smaller in bilateral legs of the PCL-d group than those of the control leg (Figure 2D). Significantly smaller hip external rotation angles were found in the uninvolved leg of the PCL-d group when compared with the involved leg of the PCL-d group and the control legs during nearly the entire stance phase (Figure 2E). Both legs of the PCL-d group had significantly larger hip internal rotation moments during the terminal stance and preswing phases compared with the control leg (Figure 2F).

Kinematics and Kinetics of the Ankle

To be consistent with the knee and hip, we expressed ankle dorsiflexion as ankle flexion and expressed ankle plantarflexion as ankle extension. Extension and adduction angles of the ankle were significantly larger in both legs of the PCL-d group than in the control legs during the loading response and midstance phases (Figure 3, A and C). Ankle flexion moments were significantly smaller in

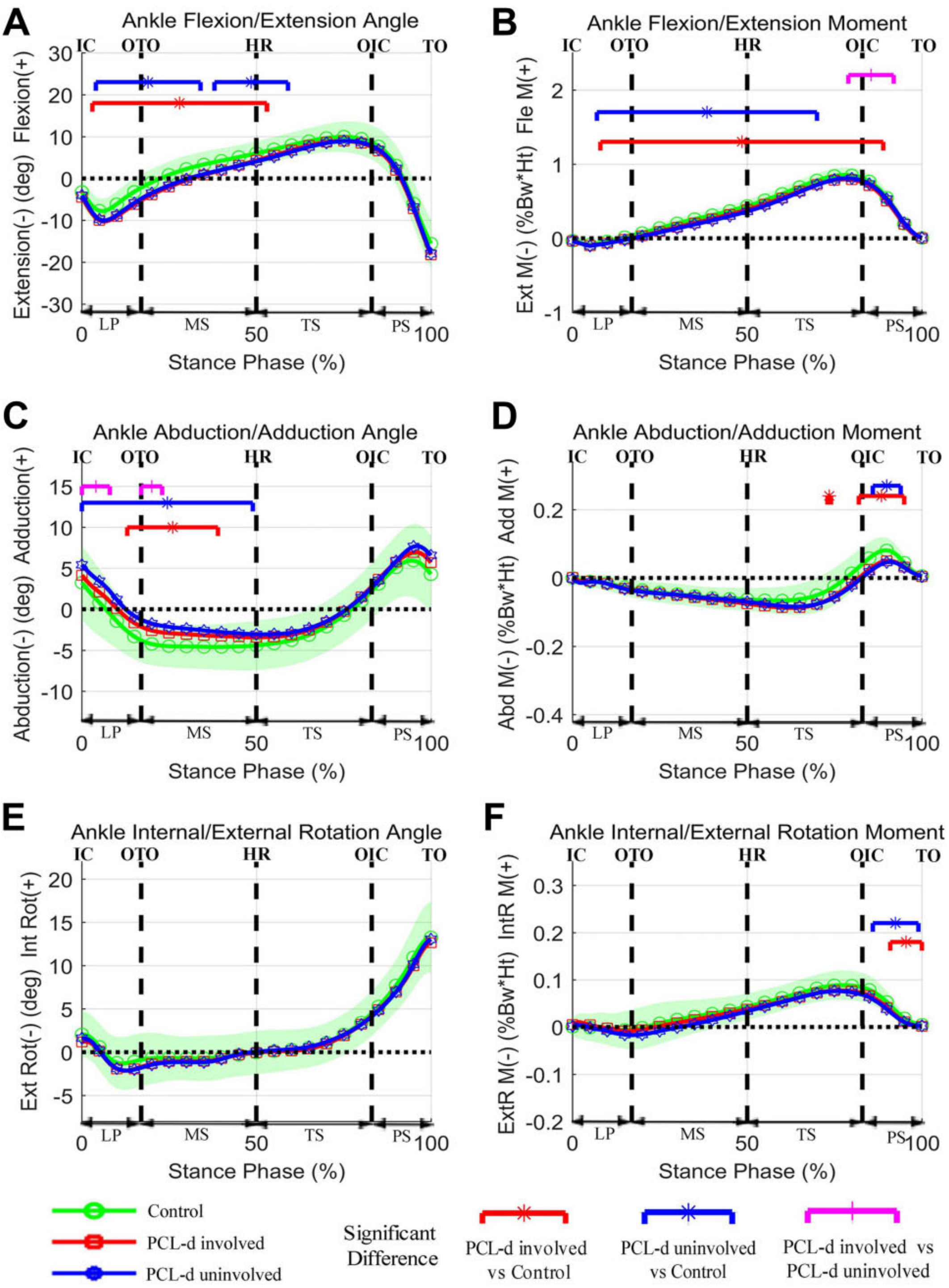

Figure 3. (A-F) The ensemble average of ankle angles and moments during the walking stance phase. The green shaded areas are the ankle angles and moments (mean ± SD) of the 27 control legs. Significant differences are marked with asterisks: $P < .05$. HR, heel rise; IC, initial contact; LR, loading response phase; MS, midstance phase; OIC, opposite initial contact; OTO, opposite toe-off; PS, preswing phase; TO, toe-off; TS, terminal stance phase.

both legs of the PCL-d group compared with the control legs during the single support phase and were smaller in the involved leg of the PCL-d group than in the uninvolved leg of the PCL-d group and the control legs during the terminal stance and preswing phases (around where opposite foot initial contact occurred) (Figure 3B). Both legs of the PCL-d group had significantly smaller ankle moments of adduction and internal rotation than the control leg

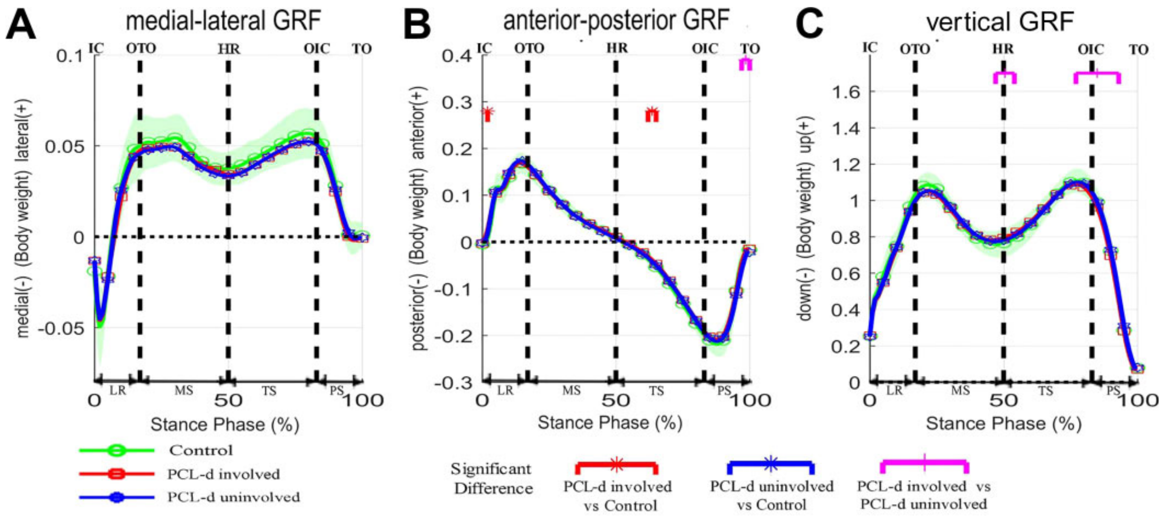

Figure 4. (A-C) The ensemble average of ground-reaction forces (GRFs) during the walking stance phase. The green shaded areas are the GRFs (mean ± SD) of the 27 control legs. Significant differences are marked with asterisks: $P < .05$. HR, heel rise; IC, initial contact; LR, loading response phase; MS, midstance phase; OIC, opposite initial contact; OTO, opposite toe-off; PS, preswing phase; TO, toe-off; TS, terminal stance phase.

during the preswing phase (Figure 3, D and F). No significant differences were found in ankle internal/external rotation angles when compared among the involved leg of the PCL-d group, the uninvolved leg of the PCL-d group, and the control leg (Figure 3E).

Ground-Reaction Force

No significant differences were found in medial/lateral GRFs when compared among the involved leg of the PCL-d group, the uninvolved leg of the PCL-d group, and the control leg (Figure 4A). Posterior GRFs were significantly smaller in the involved leg of the PCL-d group than in the control legs during the terminal stance phase and were also smaller than in the uninvolved leg of the PCL-d group during the preswing phase (Figure 4B). Significantly greater vertical GRFs were found in the involved leg of the PCL-d group than in the uninvolved leg of the PCL-d group during the midstance and terminal stance phases (around heel rise). On the contrary, significantly smaller vertical GRFs were found in the involved leg of the PCL-d group than in the uninvolved leg of the PCL-d group during the terminal stance and preswing phases (around opposite initial contact) (Figure 4C).

DISCUSSION

Most previous studies[9,11,16,28] regarding PCL ruptures have focused on knee kinematics in the sagittal plane of the PCL-deficient leg during the stance phase of walking and found no significant difference among the involved leg of the PCL-d group, the uninvolved leg of the PCL-d group, and a control group. Our study not only focused on the knee kinematics and kinetics of legs in the PCL-d group in 3D planes but also on the hip and ankle in 3D planes. This study found significant differences in the kinematics and kinetics among the involved leg of the PCL-d group, the uninvolved leg of the PCL-d group, and a control group.

Isokinetic Strength

Our strength testing demonstrated that the involved leg of the PCL-d group had less quadriceps and hamstring muscle strength compared with the uninvolved leg of the PCL-d group at 60 deg/s during knee flexion from 0° to 90°, which may be the result of a decreased mechanical advantage of the extensor mechanism secondary to posterior sag of the tibia.[3,41] With posterior subluxation of the tibia on the femur, there is a shortened moment arm, with resultant loss of strength.[3,41] Quadriceps and hamstring weakness may also be a response to the initial effusion and ensuing disuse atrophy, as the involved leg bears less weight while the uninvolved leg bears more weight after a PCL rupture. Appropriate rehabilitation exercises (strengthening the quadriceps) may help patients with PCL deficiency to achieve better outcomes.[33]

Knee Kinematics

Our results showed that knee extension angles were significantly smaller in the involved leg of the PCL-d group than in the uninvolved leg of the PCL-d group during the terminal stance phase. This finding of extension deficiency was consistent with the study of Tibone et al,[41] who observed smaller knee extension angles in the involved leg of the PCL-d group when compared with that of the uninvolved leg of the PCL-d group during fast walking.

Extension deficiency can be explained by the function of the PCL. In passive knee flexion, the strain of the PCL decreases from 0° to 30° and increases from 30° to 90°, with the smallest strain at 30° of knee flexion.[17] The PCL is stressed maximally at full extension during the stance phase of level walking.[41] Increased posterior translation was found in those patients with acute tears of the PCL when the knee was close to extension.[38] Those patients were found to be avoiding full extension to compensate for the secondary stresses on the joint and posterior capsule caused by the absent PCL, as the posterior instability would be greater in full extension than in slight flexion.[41] Therefore, extension deficiency in the involved leg of the PCL-d group during the terminal stance phase is likely to be an adaptation strategy to avoid excessive tibial posterior translation and to maintain stability of the knee.

As we know, patients with ACL disruption may cope with their knee instability by "stiffening the knee," which decreases knee flexion during gait. However, PCL-deficient patients in this study appear to have increased knee flexion during the stance phases, which is not like that seen after an ACL injury.

Knee Kinetics

Our results showed that during the terminal stance phase, extension moments were significantly smaller in the involved leg of the PCL-d group than in the uninvolved leg of the PCL-d group, which may decrease force and prevent the tibia from posterior translation during the extension movement. The study of Liu et al[28] showed that the asymptomatic PCL-deficient knee had smaller extension moments in the terminal stance than those seen in a control group, while the values of the symptomatic PCL-deficient group were closer to those of healthy participants. In our study, patients in the PCL-d group had no symptoms during level walking; therefore, knee extension deficiency could be a result of the adaptive gait pattern after a PCL rupture. Moreover, this smaller extension moment can result from decreased quadriceps strength, as Lewek et al[24] reported that inadequate quadriceps strength contributes to altered gait patterns after ACL reconstruction. In our study, we found that strength and knee extension moments in the involved leg of the PCL-d group were significantly smaller than those in the uninvolved leg of the PCL-d group. Therefore, gait changes after a PCL injury cannot be assumed to be solely related to the lost function of the ligament but can also result from muscular adaptations.

During the preswing phase, where external rotation angles of the knee were increasing, knee internal rotation moments were smaller in both legs of the PCL-d group than the control group, which means that the knee external rotator moments were smaller in both legs of the PCL-d group than the control group. One of the functions of the PCL is limiting external rotation of the tibia relative to the femur.[40] After ruptures of the PCL, there is a tendency for external rotation of the tibia to increase relative to the femur, and decreased knee external rotator moments may be an adaptive strategy to combat the tendency of the tibia to be forced outward relative to the femur.

The knee's mechanical environment during walking has been suggested to influence the health and degeneration of knee articular cartilage.[1] Wellsandt et al[44] reported that cartilage degeneration in ACL-reconstructed knees was associated with joint unloading. Chehab et al[5] demonstrated that reduced knee moments reflect a compensatory mechanism to reduce knee loading during the earliest stages of knee osteoarthritis. Therefore, it is likely that the decreased extension moments and internal rotation moments showed in this study may be correlated with the degeneration of knee cartilage.

Kinematics and Kinetics of the Hip

Our study demonstrated that both legs of the PCL-d group had larger hip flexion and adduction angles compared with the control leg group during the midstance, terminal stance, and preswing phases. These adaptations may indicate altered neuromuscular control of alignment in the lower extremities of the PCL-d group during walking. We found that hip internal rotation moments were significantly larger in both legs of the PCL-d group than those in the control legs during the terminal stance and preswing phases, which can be balanced by hip external rotator moments. As stated above, the PCL can limit external rotation of the tibia relative to the femur.[40] After ruptures of the PCL, there is a trend for internal rotation of the femur to increase relative to the tibia, and increased hip external rotator moments may be an adaptive strategy against the tendency of the femur to be forced inward relative to the tibia.

Therefore, a rupture of the PCL influences the movement of both hips. For those with insufficient gluteal muscle activation during level walking, it may be necessary to increase mobilization of the external rotation muscle during level walking to ensure that the femur is not excessively internally rotated to increase stability of the knee joint.

Kinematics and Kinetics of the Ankle

As contraction of the gastrocnemius muscle can result in extension and adduction of the ankle, the increased extension and adduction angles of the ankle on both limbs of the PCL-d group during the loading response and midstance phases in our study may be associated with earlier contraction of the gastrocnemius in PCL-deficient knees as found in previous studies.[19,41] The increased angles of the ankle may be a compensatory strategy to stabilize the unstable knee.

During the single support phase, while the ankle extension angle was not different among the involved and uninvolved legs of the PCL-d group as well as the control legs, the decrease in ankle flexion moments (decreased ankle extensor moments) may be a compensatory strategy to decrease the load on the involved leg. Ankle internal rotation moments were smaller in both legs of the PCL-d group compared with those in the control group during the preswing phase, where knee rotation moments demonstrated a similar strategy, which may be a concomitant adaptation strategy to control stability of the tibia relative to the femur.

Ground-Reaction Force

This study showed that posterior GRFs were significantly smaller in the involved leg of the PCL-d group than in the control legs during the terminal stance phase and smaller than the uninvolved leg of the PCL-d group during the preswing phase. During the terminal stance phase, the knee joint will gradually turn to maximum knee extension. During the preswing phase, knee flexion angles will reach the maximum value of the support period. PCL strain increases from knee flexion 30° to full extension and increases from 30° to 90° of knee flexion.[17] Without the stabilization from the PCL, the posterior GRFs tend to make the knee more unstable. Therefore, the reduced posterior GRFs during the terminal stance phase and the preswing phase may be adaptation strategies to avoid excessive tibial posterior displacement caused by PCL deficiency.

The involved leg of the PCL-d group had significantly smaller vertical GRFs than the uninvolved leg around opposite initial contact. This means that the involved leg had reduced vertical GRFs when the opposite uninvolved leg initially contacted the ground, which may play a role in protecting the involved side. Contrarily, significantly larger vertical GRFs were found in the involved leg of the PCL-d group than those in the uninvolved leg of the PCL-d group around heel rise. However, Fontbote et al[9] found that patients with PCL-d had significantly greater vertical GRFs in both the involved and uninvolved legs compared with a control group. The reason for the difference between our study and Fontbote et al's[9] may be because of the different participant groups focused on, as Fontbote et al[9] studied a PCL-d group with grade 3 (>10 mm) injuries, while our study examined mostly grade 2 (6.5 mm) injuries.

Clinical Relevance

Our participants with isolated PCL deficiency demonstrated significant kinematic and kinetic adaptations in the knee, hip, and ankle during level walking, which are thought to be a strategy for increasing knee stability. As Miao et al[31] demonstrated significant differences in electroencephalogram power spectra between patients with ACL deficiency and healthy people during walking, and the ACL and PCL both are crucial stable structures of the knee, adaptations in the lower limbs of the PCL-d group in this study may be related to alterations in the neuromuscular system after the PCL rupture.

We studied the knee angle (<45°) and moment of the stance phase during walking. Van de Velde et al[42,43] found no differences between the PCL-deficient leg and intact contralateral leg for the patellofemoral joint and medial compartment kinematics within 0° to 60° of knee flexion. Our study found few differences in knee kinematics within 0° to 45° knee flexion, which is overall similar to the results of Van de Velde et al[42,43]; however, we found significant differences in kinetics of the knee in the transverse and sagittal planes when we compared the PCL-deficient leg with the intact contralateral leg and the healthy control group, and the almost unchanged knee kinematics can be a result of adaptation. The alteration in kinetics that we found may have an effect on the patellofemoral joint and medial compartment, as joint moments are frequently used as measurements of joint loading.[46]

Although we observed significant differences among the involved leg of the PCL-d group, the uninvolved leg of the PCL-d group, and the control leg group during the level walking process, participants in the study exhibited no symptoms when walking. Further studies are required to clarify long-term effects on articular cartilage of the PCL-deficient leg to prevent long-term degeneration and improve the treatment outcome for PCL injuries. More functionally demanding activities, such as descending stairs, squats, lunging, and stopping quickly, may result in more altered kinematics than level ground walking.[26,42,43]

There are some limitations to this article. First, we did not further support our data and analyses using electromyography. Surface electromyography can reflect the timing and intensity of muscle contractions during dynamic exercise, which may be helpful for explaining exercise performance. Second, the movements of the pelvis and torso were not analyzed, as we found that some patients with PCL ruptures reported pain and discomfort in the lumbar spine. The effect of PCL ruptures on the lumbar spine needs to be further studied. Third, muscle strength may affect gait, but the relationship between muscle strength and gait impairments was not analyzed because of the varieties of patients' muscle strength characteristics, further research and analysis should be carried out in the future. Fourth, all of the patients were scheduled to undergo surgery, so they had "failed" nonoperative treatment and thus represent patients with worse function/more symptoms, and it is possible that patients without symptoms after nonoperative treatment might have different results.

CONCLUSION

Compared with the control leg group, both legs in the PCL-d group had smaller knee flexion and internal rotation moments; larger hip angles of flexion and adduction and moments of internal rotation; larger ankle angles of extension and adduction; and smaller ankle moments of flexion, adduction, and internal rotation. Moreover, compared with the uninvolved leg in the PCL-d group, the involved leg in the PCL-d group had significantly smaller knee extension angles and moments during the terminal stance phase, larger hip external rotation angles and extension moments, and smaller ankle adduction angles and flexion moments.

A rupture of the PCL altered walking patterns in both the involved and uninvolved legs compared with a control group and also between legs of the PCL-d group, which affected alignment of the lower limb and the load on joints of the knee, hip, and ankle. Patients with PCL injuries adapted their hip and ankle biomechanics to maintain knee stability.

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