Neuromuscular and Biomechanical Adaptations of Patients With Isolated Deficiency of the Posterior Cruciate Ligament

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Background: Functional adaptations of patients with posterior cruciate ligament deficiency (grade II) are largely unknown despite increased recognition of this injury.

Hypothesis: Posterior cruciate ligament–deficient subjects (grade II, 6- to 10-mm bilateral difference in posterior translation) will present with neuromuscular and biomechanical adaptations to overcome significant mechanical instability during gait and drop-landing tasks.

Study Design: Controlled laboratory study.

Methods: Bilateral comparisons were made among 10 posterior cruciate ligament–deficient subjects using radiographic, instrumented laxity, and range of motion examinations. Biomechanical and neuromuscular characteristics of the involved limb of the posterior cruciate ligament–deficient subjects were compared to their uninvolved limb and to 10 matched control subjects performing gait and drop-landing tasks.

Results: Radiographic (15.3 ± 2.9 to 5.6 ± 3.7 mm; $P = .008$) and instrumented laxity (6.3 ± 2.0 to 1.4 ± 0.5 mm; $P < .001$) examinations demonstrated significantly greater posterior displacement of the involved knee within the posterior cruciate ligament–deficient group. The posterior cruciate ligament–deficient group had a significantly decreased maximum knee valgus moment and greater vertical ground reaction force at midstance during gait compared to the control group. During vertical landings, the posterior cruciate ligament–deficient group demonstrated a significantly decreased vertical ground reaction force loading rate. All other analyses reported no significant differences within or between groups.

Conclusion: Posterior cruciate ligament–deficient subjects demonstrate minimal biomechanical and neuromuscular differences despite significant clinical laxity.

Clinical Relevance: The findings of this study indicate that individuals with grade II posterior cruciate ligament injuries are able to perform gait and drop-landing activities similar to a control group without surgical intervention.

Keywords: posterior cruciate ligament (PCL); knee injuries; biomechanics; neuromuscular

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The majority of the current PCL research has focused on the basic science of PCL biomechanics and PCL reconstruction. These studies have improved our understanding of the function of the PCL in the laboratory setting, delineating the role of this ligament as a static posterior stabilizer of the knee. However, very little work has been done on the in vivo adaptations of the patient with PCL injury during ambulatory conditions. The relative lack of information has contributed to inconsistent clinical management and variable outcomes in the treatment of knee injuries involving the PCL.[9,20,29,30,44]

The reported incidence of PCL injuries in the general population varies between 3% and 23% for knee joint injuries,[6,9,20,28] although it has been reported that up to

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Presented at the 29th annual meeting of the AOSSM, San Diego, California, July 2003.

No potential conflict of interest declared.

The American Journal of Sports Medicine, Vol. 33, No. 7
DOI: 10.1177/0363546504271966

40% of all knee ligament injuries seen in a trauma setting involve the PCL.[16] Injuries of the PCL may occur as isolated injuries or in combination with other knee ligament injuries. Isolated injuries have often been considered to run a "benign" clinical course and have traditionally been treated nonoperatively.[10,27,37] However, if the injury is not appropriately addressed and treated, patients with chronic PCL deficiency may develop increased knee instability and arthritic changes over time.[11,13,27,37] Unfortunately, surgical management of isolated PCL injuries has also been problematic, with a high number of patients experiencing residual posterior knee laxity.[3,9,17,24,29,36,44] Thus, the management of PCL injuries continues to present methodological and logistical challenges for the clinician.[1]

Numerous studies have been performed to examine the functional changes that develop over time in patients with ACL deficiency. Through the use of motion analysis, strength testing, and electromyography, these studies have shown that the loss of stability from the ACL results in functional adaptations in gait pattern, muscle strength, and timing of muscle activation.[2,7,15] Results from studies such as these have enhanced the clinical management of patients with ACL injury and have contributed to the improved long-term outcomes observed in recent years. However, there is a relative lack of research describing the dynamic neuromuscular and biomechanical strategies used by PCL-deficient (PCL-d) patients to maintain knee stability. It is anticipated that obtaining similar data on the neuromuscular and biomechanical characteristics of the PCL-d knee would provide a significant contribution to the management of PCL injuries.

The objective of this study was to examine the neuromuscular and biomechanical adaptations of subjects with an isolated PCL deficiency during a functional activity (gait) and a more physically demanding activity (vertical drop landing) when compared to patients with intact knees. We hypothesized that there would be significant differences within the PCL-d group when comparing radiographic stress tests, instrumented laxity, and range of motion. In addition, we hypothesized that PCL-d subjects would demonstrate significant differences in strength (knee extensors and flexors), joint kinematics, joint kinetics, and EMG activity when compared bilaterally and to matched control subjects during ambulation and while performing a vertical drop landing.

MATERIALS AND METHODS

Subjects

Our PCL-d group consisted of 10 subjects (9 men, 1 woman) with unilateral isolated grade II PCL injuries. None of the subjects had undergone surgery or had any other lower extremity injuries. Five of the subjects injured their PCLs during a fall, and the other 5 were injured during athletic competition (hockey, football, and soccer). Diagnosis was confirmed through clinical examination by an orthopaedic surgeon and MRI. Testing of patients occurred at a mean of 4 ± 6 years after injury. Ten control subjects also participated in the study and were matched according to sex, age, height, and mass. Subject characteristics are presented in Table 1. All subjects provided written informed consent before participation in accordance with the University of Pittsburgh Institutional Review Board.

TABLE 1
Subject Demographics

	Experimental Subjects (n = 10)	Control Subjects (n = 10)	P^a
Age, y	28.4 ± 12.9	30.0 ± 12.3	.88
Height, m	1.81 ± 0.07	1.78 ± 0.09	.29
Weight, kg	89.1 ± 10.2	83.7 ± 10.0	.14

[a] Independent *t* tests were performed to ensure no group differences existed between the matched subject demographics.

The experimental group underwent a clinical examination that consisted of radiographic imaging, manual laxity examination, instrumented laxity examination, and range of motion testing. Both groups underwent strength testing and a neuromuscular assessment during 2 functional tasks. Strength testing included an isokinetic and isometric assessment of the knee extensors and flexors. The neuromuscular assessment included a biomechanical and EMG analysis during gait and vertical drop-landing activities.

Radiographic Series

To quantify posterior tibial subluxation, the experimental subjects underwent bilateral radiographic stress tests using the Telos GA II stress device (Telos, Weterstadt, Germany).[33] The subject's lower extremity was positioned nonweightbearing with the knee in 90° of flexion. With the subject's femur stabilized, an 89-N load was applied to the proximal tibia in a posterior direction. All radiographs were analyzed and measured by an orthopaedic surgeon and a radiologist. The posterior displacement of the tibia was measured by comparing the position of the posterior aspect of the tibial plateau with the posterior aspect of the femoral condyles (Figure 1).

Clinical Testing

All experimental subjects underwent a clinical examination that consisted of a manual laxity examination, instrumented laxity examination, and range of motion testing. These tests were conducted bilaterally on all experimental subjects by the same orthopaedic surgeon. The laxity examination consisted of a manual test to grade posterior translation of the medial tibial plateau with respect to the medial femoral condyle.[32] Subjects were graded according to bilateral differences in translation as follows: grade I, 1 to 5 mm; grade II, 6 to 10 mm; grade III, >10 mm. Additional manual tests were performed to screen out concomitant knee injuries that might compromise test results. These tests included the Lachman test, anterior drawer test, varus and valgus stress testing at full extension and

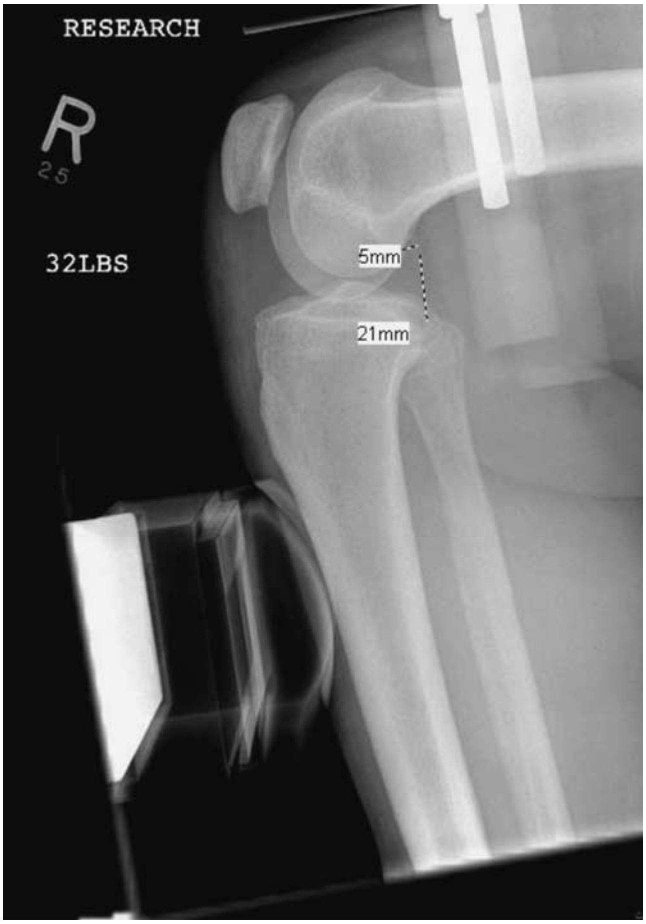

Figure 1. Radiographic stress test using the Telos GA II stress device.

20° of flexion, and dial test at 30° and 90° of flexion. Instrumented laxity testing was performed using the KT-1000 knee ligament arthrometer (MEDmetric Inc, San Diego, Calif). Posterior displacement was measured at the quadriceps neutral angle as described by Daniel et al.[12] Passive and active range of motion data were collected with a universal goniometer for both knee flexion and extension according to Norkin and White.[35]

Strength Assessment

All subjects underwent strength testing using the Biodex System 3 Multi-joint Testing and Rehabilitation System (Biodex Medical Inc, Shirley, NY). Maximum knee flexor and extensor strength data were collected during isokinetic (60 and 240 deg/s) and isometric test modes. For isometric testing, the subject's knee was positioned at 60° of flexion. All strength tests were carried out with the subject in a seated position according to the manufacturer's specifications.

Biomechanical and Neuromuscular Assessment

A biomechanical and neuromuscular assessment was performed during a functional task (gait) and a more physically demanding task (vertical drop landing). The biomechanical assessment was performed using the Peak Motus 3D Optical Capture System (Peak Performance Technologies Inc, Englewood, Colo) interfaced with 2 Kistler force plates (Kistler Instrument Corp, Amherst, NY) with a sampling rate of 1200 Hz. Three-dimensional coordinate data of 15 retroreflective markers (modified Helen-Hayes marker set[26]) were collected through 6 high-speed (120-Hz) cameras. An inverse-dynamics procedure based on that of Vaughan et al was used to calculate joint angles and the resultant joint moments and forces during gait and the vertical drop landings.[45]

Surface EMG data were collected on 6 muscles using the Noraxon Telemyo System (Noraxon USA Inc, Scottsdale, Ariz). The 6 muscles included the vastus lateralis, vastus medialis, lateral hamstring, medial hamstring, and both heads of the gastrocnemius. The EMG activity of these muscles was recorded unilaterally with silver-silver chloride, pregelled bipolar surface electrodes (Medicotest Inc, Rolling Meadows, Ill) placed over the appropriate muscle belly perpendicular to the direction of the fibers with a center-to-center distance of approximately 20 mm.[14] Electrode site preparation to minimize impedance included removal of hair, skin abrasion, and cleaning with isopropyl alcohol. Proper electrode placement was verified through manual muscle testing. A 5-second maximum voluntary isometric contraction (MVIC) was collected for each muscle being tested for normalization of EMG during functional testing.

Each subject was provided instruction regarding the 2 functional activities and was allowed to practice each task until he or she could perform it successfully. For gait, subjects were asked to walk at a self-selected speed. A total of 10 trials of gait were collected for each subject, with the first 5 successful trials being selected for future processing. A successful trial was defined as a trial with proper foot placement on each force plate without noticeable modification of step length (Figure 2).

For the vertical drop landings, subjects performed a single-leg landing from a height of 30 cm. Subjects were instructed to maintain the untested lower extremity nonweightbearing throughout the task. After a verbal cue, subjects were asked to drop off of the platform and land on the force plate (Figure 3). On landing, subjects were instructed to maintain balance for 5 seconds. No other instruction was provided. A total of 5 trials were collected, with the first 3 successful trials being selected for future processing. A successful trial was defined as a trial with proper placement of the foot on the force plate, maintenance of the nontested lower extremity in a nonweightbearing position, and no loss of balance during the first 5 seconds after landing.

DATA ANALYSIS

For the radiographic results, the amount of translation of the tibia with respect to the femur was compared bilaterally within the experimental group. Bilateral comparisons within the experimental group were also performed for the manual laxity examination, instrumented laxity examina-

Figure 2. Gait analysis.

tion, and range of motion testing. The results of the strength tests (peak torque normalized to body weight) were compared between limbs within the experimental group and between the involved leg of the experimental group and the matched leg of the control group.

Three-dimensional coordinate data were filtered using an optimal cutoff frequency as described by Jackson.[25] Force plate data were filtered with a Butterworth filter (fourth-order, zero-phase lag, 100-Hz cutoff). Joint angles, resultant joint moments and forces, and ground reaction forces were analyzed during the stance phase of gait with comparisons made between limbs in the experimental group and between the involved leg of the experimental group and the matched leg of the control group. Joint angles, resultant joint moments and forces, and ground reaction forces were analyzed at initial contact and at peak vertical ground reaction force for the vertical drop landings. Joint resultant moments were normalized to body weight × height, and joint resultant forces were normalized to body weight.[46] In addition, the loading rate of the vertical ground reaction force was calculated. Comparisons were made between limbs in the experimental group and between the involved leg of the experimental group and the matched leg of the control group.

The EMG activity was first processed using a hardware filter to eliminate noise and artifact movement (Butterworth, 15-Hz low pass, 500-Hz high pass, common mode rejection ratio of 130 dB). The EMG data were then rectified and filtered using a Butterworth filter (fourth-order, zero-phase lag, 20-Hz cutoff). After filtering, the mean of the MVIC data was calculated for normalization of the trial data. The mean EMG and integrated EMG (IEMG) values for each subject's gait trial were calculated during 1 gait cycle and averaged across 5 trials for each subject. The IEMG values were calculated during the 150 milliseconds before initial contact (preactivity phase) and 150 milliseconds after initial contact (reactivity phase) for the vertical drop landings. Values were averaged across 3 trials for each subject. The EMG variables were compared between limbs in the experimental group and between the involved limb of the PCL-d group and the matched limb of the control group.

Figure 3. Vertical drop landing.

The Stata 8 statistical software package (Stata Corp, College Station, Tex) was used for analysis of all data. The Wilcoxon signed rank test was used to make comparisons between legs of the involved group for the radiographic and clinical examination results. A Kruskal-Wallis 1-way analysis of variance by ranks was used to make comparisons between legs within the experimental group and with the matched leg of the control group for results of the strength testing, biomechanical analysis, and EMG analysis. The *P* level for statistical significance was set at .05 for all data analysis a priori.

RESULTS

Radiographic Series

Radiographic examination revealed that the experimental group had significantly greater posterior translation of the involved knee compared to the uninvolved knee during the radiographic stress test ($P = .008$). Posterior tibial translation for the involved side was 15.3 ± 2.9 mm, and posterior tibial translation for the uninvolved side was 5.6 ± 3.7 mm.

Clinical Testing

Manual examination revealed that all of the experimental subjects had a grade II laxity (6-10 mm) of the involved

TABLE 2
Summary of Results for Instrumented Laxity and Range of Motion Testing

	Involved Knee (n = 10)	Uninvolved Knee (n = 10)	*P*
Instrumented laxity, mm	6.3 ± 2.0	1.4 ± 0.5	<.001
Passive extension, deg	4.7 ± 3.8	–3.8 ± 4.2	.384
Active extension, deg	–2.1 ± 5.2	–0.7 ± 4.2	.222
Passive flexion, deg	142.0 ± 4.3	141.1 ± 7.6	.505
Active flexion, deg	143.3 ± 7.0	141.8 ± 8.1	.299

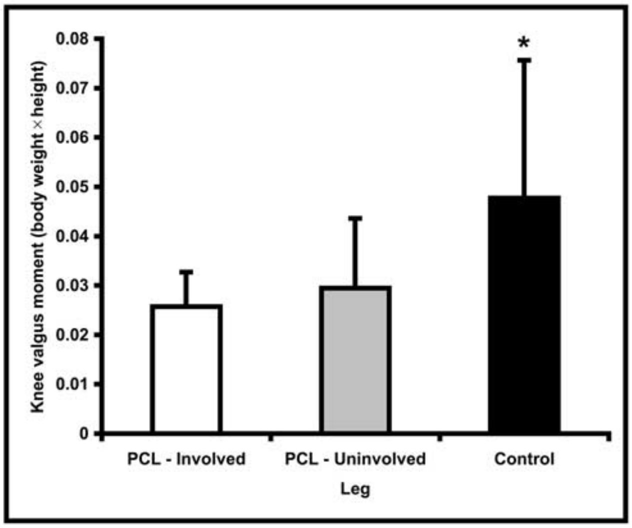

Figure 4. Results from the gait analysis. The PCL-deficient subjects demonstrated significantly less maximum knee valgus moment during the stance phase. **P* < .05.

knee. The results of the instrumented laxity examination and the range of motion testing are presented in Table 2. The PCL-d subjects had significantly greater posterior displacement (*P* = .005) for the involved knee than for the uninvolved knee. Statistical analysis did not reveal any significant differences between knees in passive extension (*P* = .384), active extension (*P* = .222), passive flexion (*P* = .505), or active flexion (*P* = .299).

Strength Assessment

Table 3 summarizes the results of the strength testing. Statistical analysis did not reveal any significant differences between legs within the PCL-d group or between the involved leg of the PCL-d group and the matched leg of the control group.

Biomechanical and Neuromuscular Assessment

For gait, there were significant differences between groups in the maximum valgus moment during the stance phase (*P* = .033) and the vertical ground reaction force at midstance (*P* = .019). The maximum valgus moment during the stance phase was significantly less in the PCL-d group's involved leg and uninvolved leg compared to the control group (Figure 4). No difference was observed between legs in maximum valgus moment during the stance phase in the PCL-d group. At midstance, the PCL-d group had a significantly greater vertical ground reaction force in both the involved leg and uninvolved leg compared to the control group: 0.78 (involved) and 0.78 (uninvolved) compared to 0.70 (control) × body weight. No difference was observed between legs in vertical ground reaction force in the PCL-d group. No differences were observed in the knee flexion during gait within the PCL-d group or between PCL-d and control group. There were no significant differences in mean or IEMG during gait between legs within the PCL-d group or between the PCL-d group and control group.

For the vertical drop landings, the PCL-d subjects demonstrated a significantly decreased loading rate in both the involved leg and uninvolved leg compared to the control group (*P* = .009). The vertical ground reaction loading rate was 60.5 body weight/s for the PCL-d group's involved leg and 58.2 body weight/s for the uninvolved leg compared to 94.4 body weight/s for the control group. No difference was observed between legs in loading rate in the PCL-d group. There were no significant differences for the

TABLE 3
Summary of Results for Strength Testing

	Experimental Group (n = 10)			
Peak Torque/Body Weight	Involved Leg	Uninvolved Leg	Control Group (n = 10)	*P*
Isokinetic extension at 240 deg/s	149.3 ± 33.5	150.1 ± 37.6	153.0 ± 31.6	.9805
Isokinetic flexion at 240 deg/s	108.0 ± 20.7	116.7 ± 25.5	111.3 ± 30.5	.8358
Isokinetic extension at 60 deg/s	211.9 ± 36.6	229.9 ± 49.6	231.9 ± 47.4	.5610
Isokinetic flexion at 60 deg/s	118.3 ± 21.4	125.9 ± 26.6	112.9 ± 30.2	.5839
Isometric extension	207.9 ± 48.1	216.3 ± 49.9	225.2 ± 37.7	.7735
Isometric flexion	102.1 ± 28.4	99.1 ± 28.2	106.8 ± 20.9	.8177

IEMG values during the preactivity phase or the reactivity phase for any of the muscles examined between legs within the PCL-d group or between the PCL-d group and control group.

DISCUSSION AND CONCLUSION

It has clearly been shown that the PCL is the primary restraint to posterior tibial translation in the knee.[8,18,19,22] Deficiency of the PCL has been shown to increase posterior tibial translation by an average of 10 mm in a cadaveric model in response to a 100-N posterior tibial load. Increased posterior tibial translation alters normal joint congruity and decreases the load accepted by the posterior horn of the medial meniscus. Deficiency of the PCL also increases the forces on other knee-supporting structures,[34] and at the same time, it increases joint reactive forces in the medial and patellofemoral compartment.[31,42] These data support the clinical observation of progressive osteoarthritis and increased joint laxity over time in patients with chronic PCL injuries.

Studies have also been performed to examine the biomechanics of various PCL reconstructions. Most recently, the techniques studied have included the tibial inlay, single-bundle transtibial, and double-bundle transtibial reconstructions. Although controversy still exists regarding which technique is most effective in restoring normal knee stability, all have been shown to reduce posterior tibial translation to within 0 to 2 mm of the intact PCL in response to a posterior tibial load.[4,5,21,38] However, the limited data concerning long-term results after PCL reconstruction and the lack of a clear demonstration of substantial functional improvement when comparing operative versus nonoperative treatments have contributed to the lack of interest in the surgical reconstruction of the PCL.[40] Therefore, many patients continue to be treated nonoperatively with bracing and a rehabilitation program of quadriceps strengthening after PCL injury.

There are few previous studies reporting on the functional characteristics of patients with PCL deficiency. One study by Safran et al examined the proprioceptive function and contributions of the PCL and demonstrated that PCL-injured subjects had a decreased ability to detect passive motion.[39] In 1988, Tibone et al[43] carried out a study of 20 PCL-d patients who were divided into operative (surgical transfer of the head of the gastrocnemius) and nonoperative groups. There was no "normal" or control group as was included in this study. The aim of the study was to find any adaptive differences between the 2 groups. The patients underwent a series of functional examinations, including gait analysis, video-motion analysis, and muscle analysis using surface EMG. Even though there were biomechanical abnormalities in all the patients, the authors did not find significant differences between the 2 groups.

Shirakura et al[41] examined the isokinetic strength of the quadriceps muscle group in patients with cruciate ligament injury, finding significant deficiencies in peak concentric and eccentric torques between involved and uninvolved limbs, as well as all torques measured at flexion angles greater than 36° in the subjects with a unilateral PCL injury. The authors concluded that quadriceps strength in PCL-d patients was most compromised at higher flexion angles. Fleming et al reported on their observations that patients with chronic PCL deficiency tend to walk with a bent knee gait to avoid terminal hyperextension and external rotation of the tibia on the femur due to posterior subluxation of the lateral tibial plateau.[17] Inoue et al recently studied the electrical activity of the quadriceps, hamstrings, and gastrocnemius in patients with chronic PCL deficiency, comparing the PCL-d and the normal contralateral knee. There were no significant differences in the muscular activation of the quadriceps and hamstrings, but the authors reported earlier contraction of the gastrocnemius in the PCL-d knees.[23]

In the present study, we originally hypothesized that an isolated PCL injury and resultant posterior laxity would cause compensatory changes and that PCL-d subjects would demonstrate significant differences in strength (knee extensors and flexors), joint kinematics, joint kinetics, and EMG activity when compared to normal controls during ambulation and while performing a vertical drop landing. In contrast to the findings of Shirakura et al,[41] during strength testing, we demonstrated no differences between limbs in the PCL-d group or between the PCL-d group and the control group. Our gait analysis testing demonstrated that PCL-d patients had a decreased valgus moment during the stance phase and significantly greater vertical ground reaction forces at midstance compared to the control group. Both of these differences were observed bilaterally in the PCL-d group when compared to the control group, but they were not bilaterally different within the PCL-d group. The reasons for this finding are not clear, but it may be owing to a lack of control in gait speed during testing. Subjects were asked to walk at a self-selected, comfortable speed. If the PCL-d group walked slower than the control group did, then their ground reaction forces would have been lower and may have influenced the knee joint resultant moments. In the present study, we did not demonstrate a flexed knee gait pattern as Fleming et al have previously observed.[17] This finding may be owing to the time of follow-up. The study group of Fleming et al had a mean follow-up of 16 months, with some of their subjects still in the rehabilitative phase, compared to the mean of 48 months in the present study. Finally, we observed IEMG findings that were similar to the findings of Inoue et al,[23] in that there were no significant differences in mean or IEMG of the quadriceps, hamstrings, and gastrocnemius during gait between groups.

During vertical drop-landing testing, PCL-d subjects demonstrated significantly less vertical ground reaction loading rates compared to control subjects. This difference was observed bilaterally in the PCL-d group, but it was not significantly different between limbs within the PCL-d group. Most likely, this difference was observed in the PCL-d group as they attempted to decrease the impact when landing from the 30-cm height, although there were no significant differences observed in kinematic data that would explain the method behind this strategy. Muscle activity analysis also did not reveal any significant differences between groups or between legs within the PCL-d group for the IEMG values of the quadriceps, hamstrings, and gastrocnemius during the preactivity phase or the reactivity phase for any of the muscles examined.

Our subjects with an isolated chronic PCL deficiency demonstrated few kinematic and kinetic adaptations during functional activities such as walking and/or during more physically demanding activities such as a vertical drop landing. The relative lack of observed differences may have been the result of differences between the 2 groups that were not controlled for during selection of the control subjects. For instance, current activity level or athletic history was not determined in the PCL-d group and was not controlled for in the control group. This factor may explain why some of the results were bilaterally equal in the PCL-d group and significantly different compared to the control group. Another potential reason for observing few compensatory adaptation differences between groups may be the choice of activities studies—gait and vertical drop landings. Analysis of other activities such as running, cutting, or stop-jump tasks may reveal differences between PCL-d individuals and healthy control subjects. The results of this study suggest that few adaptations are necessary for the performance of the tasks that were studied, which may allow PCL-d individuals to be physically active without experiencing symptoms of instability.

FUTURE DIRECTIONS

The results of our study form the groundwork and provide us with the basic information needed to perform future studies. The data obtained and testing sequences developed in this initial study will allow us to evaluate the functional performance and biomechanical adaptations in subjects with a chronic, isolated grade III PCL deficiency; subjects with combined PCL injuries (ie, PCL and posterolateral corner); and subjects who have undergone PCL reconstruction surgery.

ACKNOWLEDGMENT

This study was supported by grants from the Arthroscopy Association of North America and the Albert Ferguson Jr Orthopaedic Foundation.

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