Research Report

Lower-Extremity Compensations Following Anterior Cruciate Ligament Reconstruction

Background and Purpose. Several studies have demonstrated that patients with knee injury scored within a normal range during one-legged hop tests yet showed quadriceps femoris muscle weakness with non–weight-bearing isokinetic testing. This study evaluated lower-extremity kinetics while subjects performed a single-leg vertical jump (VJ) and a lateral step-up (LSU) in an attempt to explain this phenomenon. **Subjects and Methods.** Using a motion analysis and force platform system, hip, knee, and ankle extension moments of 20 subjects with anterior cruciate ligament (ACL) reconstructions and 20 matched subjects were measured while they performed an LSU and a VJ. **Results.** An analysis of variance revealed that the knee extension moment of the ACL-reconstructed extremity was lower than that of the uninjured and matched extremities during the LSU, VJ take-off, and VJ landing. However, there was no difference in summated extension moment (hip + knee + ankle) among extremities during the LSU and VJ take-off. The summated extension moment of the ACL-reconstructed extremity during VJ landing was less than that of the uninvolved and matched extremities. **Conclusions and Discussion.** These results suggest that the hip or ankle extensors may compensate for the knee extension moment deficit. The decrease in summated extension moment in the ACL-reconstructed extremity during VJ landing represents inadequate attenuation of landing forces, which may expose the skeleton and joint structures to injury. [Ernst GP, Saliba E, Diduch DR, et al. Lower-extremity compensations following anterior cruciate ligament reconstruction. *Phys Ther.* 2000;80:251–260.]

Key Words: *Anterior cruciate ligament reconstruction, Compensations, Functional tests, Lower-extremity kinetics.*

Gregory P Ernst

Ethan Saliba

David R Diduch

Shepard R Hurwitz

Donald W Ball

The anterior cruciate ligament (ACL) is the most commonly injured ligament in the knee.[1] Injury to the ACL results in pain, instability, and difficulty with recreational and athletic activities. In the preferred method of surgical reconstruction of the ACL, the middle one third of the patellar tendon is taken from the patient's injured knee and placed at the anatomic location that the native ACL occupied prior to injury.[2] Surgical reconstruction of the ACL improves the mechanical stability of the knee to allow the individual to return to an active lifestyle. The added stability may also prevent progressive knee joint laxity and degenerative changes that often occur with instability.[3–7] In the late 1980s, the use of the arthroscope and improved fixation methods combined with early and aggressive rehabilitation protocols resulted in improved outcomes in people with ACL reconstructions.[8–10] However, quadriceps femoris muscle weakness and knee extensor dysfunction frequently occur.[11–19]

Tests such as the vertical jump (VJ), hop for distance, and timed hop are used to provide an assessment of overall function of patients following knee injury or surgery. However, these tests do not allow the assessment of isolated knee extensor function during these weight-bearing activities. In the VJ, for example, the function of the knee extensor mechanism is assessed, but the movement also requires use of the hip extensors and ankle plantar flexors. Thus, we believe that an individual may attain a high score due to strong hip and ankle muscles rather due to than strong knee extensors. Therefore, reliance on tests involving movement may not effectively assess the knee extensor mechanism. A normal test, in our opinion, may occur even when quadriceps femoris muscle weakness exists. This apparent discrepancy is supported by the results of several studies in which patients with injured knees were able to score within 85% of the uninvolved extremity in single-leg hop tests yet have quadriceps femoris muscle weakness as measured in a non–weight-bearing position with an isokinetic device.[20–22] Wilk et al[22] reported that 50% of subjects 6 months after ACL reconstruction scored within the normal range (85% of the uninvolved extremity) for single-legged hop tests and only 7% scored within the normal range (within 90% of the uninvolved extremity) in gravity-corrected quadriceps femoris muscle isokinetic strength tests at 180° and 300°/s.

Researchers have used kinetic and kinematic analyses in an attempt to assess lower-extremity joint function while subjects performed functional activities such as walking or climbing stairs.[23–25] Kinetic studies of the knee sometimes use the internal knee extension moment as the variable of interest.[23–25] The internal knee extension moment is the torque produced by the knee extensors in response to the tendency of the body's center of mass to flex the knee.[26] Berchuck et al[23] found a marked decrease in the internal knee extension moment during the loading phase of walking in subjects with ACL-deficient knees.

We contend that, although the neuromuscular system is able to compensate for a knee extension moment deficit, this compensation may not always be beneficial. The use

GP Ernst, PT, PhD, SCS, ATC, is a Commander in the Medical Service Corps, US Navy, and Assistant Professor, US Army–Baylor University Graduate Program in Physical Therapy, Fort Sam Houston, TX. Address all correspondence to CDR Ernst at 182 Artillery Post Rd, Fort Sam Houston, TX 78234 (USA) (gernst1@juno.com).

E Saliba, PT, PhD, SCS, ATC, is Assistant Professor in the Department of Human Services, Curry School of Education, University of Virginia. He is also Head Athletic Trainer at the University of Virginia.

DR Diduch, MD, is Assistant Professor of Orthopedic Surgery at the University of Virginia.

SR Hurwitz, MD, is Associate Professor of Orthopedic Surgery at the University of Virginia.

DW Ball, PhD, is Professor in Educational Studies, Curry School of Education, University of Virginia.

Dr Mark Abel made the motion analysis laboratory at Kluge Children's Rehabilitation Center available for this study. Joe Gieck, PT, EdD, and David Perrin, PhD, ATC, also provided assistance.

This research was completed in partial fulfillment of CDR Ernst's Doctor of Philosophy degree at the University of Virginia.

This study was approved by the Institutional Review Board at the University of Virginia.

This paper was presented as a platform presentation at Physical Therapy '98: APTA Scientific Meeting and Exposition; June 6, 1998; Orlando, Fla.

The opinions expressed herein are those of the authors and do not necessarily reflect the opinions of the Department of Defense, the United States Navy, or other federal agencies.

This article was submitted June 22, 1998, and was accepted October 12, 1999.

of lower-extremity weight-bearing exercises, such as the lateral step-up (LSU), is common in knee rehabilitation programs.[27] When knee pain or effusion is present, there may be reflex inhibition of the quadriceps femoris muscle, thus preventing full activation of this muscle.[28] In our opinion, when a patient performs an LSU, the ipsilateral hip extensors or the soleus muscle may compensate for the quadriceps femoris muscle deficit and increase their contribution to knee extension. This compensation would lessen the demand on the quadriceps femoris muscle and markedly reduce the strengthening effect of this exercise on the quadriceps femoris muscle.

The purpose of our study was to evaluate lower-extremity kinetics following autograft bone-patellar tendon-bone ACL reconstruction while subjects performed an LSU and a VJ. Our aim was to determine whether deficits in the ability of the quadriceps femoris muscle to generate an extension moment at the knee during a VJ or an LSU would be compensated for by the hip and ankle musculature. We examined the effect of ACL reconstruction and the type of activity (LSU or VJ) on knee extensor moment and summated extensor moment (hip + knee + ankle extensor moments) for the lower extremity. The following hypotheses were tested for 3 weight-bearing activities (ie, LSU, VJ take-off, and VJ landing): (1) the knee extension moment for the reconstructed extremity would be less than that of the contralateral extremity and those of the limbs of a comparison group, and (2) there would be no difference in the summated extension moment between the ACL-reconstructed limb, the contralateral limb, and the limbs of the comparison group. A normal summated extensor moment in the presence of a knee extensor moment deficit, in our opinion, would indicate that the hip or ankle extensor moment increased to compensate for the knee deficit.

Secondarily, we wanted to examine the relationship between forward leaning of the trunk and knee extensor moments during the VJ and LSU. This was done to substantiate the relationship between trunk flexion angle and knee extension moment reported by Berger et al.[25] They found that, as the degree of forward trunk leaning increased, the internal hip extension moment increased and the internal knee extension moment decreased. If we found such an increase in hip extension moment with a decrease in knee extension moment in our subjects, we wanted to determine whether the degree of forward trunk leaning was related to changes in the hip and knee extension moments. If there was no relationship, we could consider reasons other just than a change in trunk leaning to explain our findings. Finally, because pain inhibition may be present in the subjects with ACL reconstructions, we wanted to determine whether pain was associated with any knee extensor moment deficit. If a knee extension moment deficit was found to be present, we wanted to be able to determine whether this deficit was related to pain or to other factors. Therefore, our third hypothesis was that we expected an inverse relationship between forward trunk leaning and knee extensor moment and between pain and knee extensor moment.

The independent variables were (1) group (subjects with ACL reconstructions or comparison subjects), (2) extremity (ACL-reconstructed extremity, contralateral uninjured extremity, or the extremities of the uninjured matched comparison subjects), and (3) activity (LSU, VJ take-off, or VJ landing). The dependent variables were (1) the maximal knee extension moment (in newton-meters per kilogram) and (2) the summated extension moment (maximal hip + knee + ankle extension moments). The degree of forward trunk leaning and pain were measured to address the third hypothesis.

Method

Subjects

Kinetic analysis was performed on 20 subjects (14 male, 6 female), with a mean age of 23.5 years (SD=3.7, range=19–29), a mean of 9.8 months (SD=2.3, range=8–15) after ACL reconstruction was done using a graft obtained from the central third of each subject's patellar tendon. Sixteen of the subjects with ACL reconstructions were consecutive cases from one orthopedic surgeon, and the remaining 4 subjects were from another orthopedic surgeon from the same academic medical center. All subjects followed alike rehabilitation protocols that used both weight-bearing and non–weight-bearing exercises. A comparison subject of the same sex and approximate age, weight, and activity level was recruited for each subject with an ACL reconstruction (Tab. 1). Both groups of subjects underwent identical testing. The Tegner and Lysholm Activity Scale[29] was used to match the comparison and experimental subjects based on activity level. The Tegner and Lysholm Activity Scale is a scale ranging from 0 to 10, with 0 meaning the individual is disabled due to a knee condition and 10 meaning the individual is a competitive athlete. Comparison subjects had to be at the same level or one level above or below that of their matched subjects with ACL reconstructions.

All subjects with ACL reconstructions had no history of surgery or traumatic injury to the uninvolved lower extremity or to the hip or ankle of the involved lower extremity, no more than one surgery for a tear of the ACL, no other ligamentous injury in the operated knee, and no history of any medical problem in the 4 weeks prior to testing. In addition, we examined all knees of all subjects with ACL reconstructions with the KT-1000 of lower-extremity weight-bearing exercises, such as the lateral step-up (LSU), is common in knee rehabilitation programs.[27] When knee pain or effusion is present, there may be reflex inhibition of the quadriceps femoris muscle, thus preventing full activation of this muscle.[28] In our opinion, when a patient performs an LSU, the ipsilateral hip extensors or the soleus muscle may compensate for the quadriceps femoris muscle deficit and increase their contribution to knee extension. This compensation would lessen the demand on the quadriceps femoris muscle and markedly reduce the strengthening effect of this exercise on the quadriceps femoris muscle.

The purpose of our study was to evaluate lower-extremity kinetics following autograft bone-patellar tendon-bone ACL reconstruction while subjects performed an LSU and a VJ. Our aim was to determine whether deficits in the ability of the quadriceps femoris muscle to generate an extension moment at the knee during a VJ or an LSU would be compensated for by the hip and ankle musculature. We examined the effect of ACL reconstruction and the type of activity (LSU or VJ) on knee extensor moment and summated extensor moment (hip + knee + ankle extensor moments) for the lower extremity. The following hypotheses were tested for 3 weight-bearing activities (ie, LSU, VJ take-off, and VJ landing): (1) the knee extension moment for the reconstructed extremity would be less than that of the contralateral extremity and those of the limbs of a comparison group, and (2) there would be no difference in the summated extension moment between the ACL-reconstructed limb, the contralateral limb, and the limbs of the comparison group. A normal summated extensor moment in the presence of a knee extensor moment deficit, in our opinion, would indicate that the hip or ankle extensor moment increased to compensate for the knee deficit.

Secondarily, we wanted to examine the relationship between forward leaning of the trunk and knee extensor moments during the VJ and LSU. This was done to substantiate the relationship between trunk flexion angle and knee extension moment reported by Berger et al.[25] They found that, as the degree of forward trunk leaning increased, the internal hip extension moment increased and the internal knee extension moment decreased. If we found such an increase in hip extension moment with a decrease in knee extension moment in our subjects, we wanted to determine whether the degree of forward trunk leaning was related to changes in the hip and knee extension moments. If there was no relationship, we could consider reasons other just than a change in trunk leaning to explain our findings. Finally, because pain inhibition may be present in the subjects with ACL reconstructions, we wanted to determine whether pain was associated with any knee extensor moment deficit. If a knee extension moment deficit was found to be present, we wanted to be able to determine whether this deficit was related to pain or to other factors. Therefore, our third hypothesis was that we expected an inverse relationship between forward trunk leaning and knee extensor moment and between pain and knee extensor moment.

The independent variables were (1) group (subjects with ACL reconstructions or comparison subjects), (2) extremity (ACL-reconstructed extremity, contralateral uninjured extremity, or the extremities of the uninjured matched comparison subjects), and (3) activity (LSU, VJ take-off, or VJ landing). The dependent variables were (1) the maximal knee extension moment (in newton-meters per kilogram) and (2) the summated extension moment (maximal hip + knee + ankle extension moments). The degree of forward trunk leaning and pain were measured to address the third hypothesis.

Method

Subjects

Kinetic analysis was performed on 20 subjects (14 male, 6 female), with a mean age of 23.5 years (SD=3.7, range=19–29), a mean of 9.8 months (SD=2.3, range=8–15) after ACL reconstruction was done using a graft obtained from the central third of each subject's patellar tendon. Sixteen of the subjects with ACL reconstructions were consecutive cases from one orthopedic surgeon, and the remaining 4 subjects were from another orthopedic surgeon from the same academic medical center. All subjects followed alike rehabilitation protocols that used both weight-bearing and non–weight-bearing exercises. A comparison subject of the same sex and approximate age, weight, and activity level was recruited for each subject with an ACL reconstruction (Tab. 1). Both groups of subjects underwent identical testing. The Tegner and Lysholm Activity Scale[29] was used to match the comparison and experimental subjects based on activity level. The Tegner and Lysholm Activity Scale is a scale ranging from 0 to 10, with 0 meaning the individual is disabled due to a knee condition and 10 meaning the individual is a competitive athlete. Comparison subjects had to be at the same level or one level above or below that of their matched subjects with ACL reconstructions.

All subjects with ACL reconstructions had no history of surgery or traumatic injury to the uninvolved lower extremity or to the hip or ankle of the involved lower extremity, no more than one surgery for a tear of the ACL, no other ligamentous injury in the operated knee, and no history of any medical problem in the 4 weeks prior to testing. In addition, we examined all knees of all subjects with ACL reconstructions with the KT-1000

Table 1.
Descriptive Statistics for Subjects With Anterior Cruciate Ligament (ACL) Reconstructions and Matched Comparison Subjects

Variable	Subjects With ACL Reconstructions (n=20)			Comparison Subjects (n=20)		
	$\overline{X}$	SD	Range	$\overline{X}$	SD	Range
Age (y)	23.5	3.7	19–29	22.7	4.2	20–28
Height (cm)	173.5	8.6	160–185	173.9	7.8	162–185
Weight (kg)	78.2	12.5	62–105	74.8	10.9	56–98
Males/females	14/6			14/6		
Activity score[a]						
Preinjury	7.0	1.0	5–8	...[b]		
Current	5.4	1.4	4–8	5.95	1.4	4–9
Time since surgery (mo)	9.8	2.3	8–15	...		
KT-1000 score (mm) (involved extremity – uninvolved extremity)	0.93	1.5	0.2–3.2	...		

[a] From the Tegner and Lysholm Activity Scale.[29]
[b] Ellipsis indicates not applicable or not measured in uninjured matched subjects.

knee arthrometer* to ensure that these subjects had stable knees. Those subjects with a difference between the involved and uninvolved extremities greater than 4 mm were excluded from the study to remove the potential confounding variable of knee instability. Though this difference of 4 mm is not evidence based, we did not want to consider knee laxity as a factor when examining reasons for differences between groups. Comparison subjects met the same criteria as the subjects with ACL reconstructions with the exception that they had no current or past injury that caused pain or affected their activity level to either lower extremity. All subjects signed an informed consent agreement prior to participation in the study.

Instrumentation

Data collection was performed at a gait analysis laboratory using the Vicon Motion Analysis System.† The system consisted of 6 charged coupled device cameras, a force platform,‡ a personal computer, and the accompanying Vicon software. Seventeen 1-cm plastic balls covered in reflective tape were used as body surface markers, with the thigh and calf markers attached to the end of a 6-cm-long wand per standard procedure, as recommended by the manufacturer.[30] The pelvis, knee, ankle, and shoulder markers were attached to the skin with double-sided tape, and the wands were secured around the thigh and calf with elastic tape. The cameras captured data at a frequency of 60 Hz, and the force plate sampled data at 1,200 Hz. The system was calibrated according to the manufacturer's instructions prior to each data collection session.

* MEDmetric Corp, 7542 Trade St, San Diego, CA 92121.
† Oxford Metrics, 14 Minns Estate, West Way, Oxford, England OX2 OJB.
‡ Kistler, PO Box 304, CH8408, Winterthur, Switzerland.

Procedure

Subjects reported to the gait analysis laboratory for data collection. After completing the activity questionnaire, each subject warmed up by jogging in place for 3 minutes. The reflective balls were placed on the lower extremities as described in the Vicon reference manual.[30] These locations were the anterior superior iliac spines, sacrum, lateral thighs and calves, lateral knee joint lines, lateral malleoli, posterior calcanei, and heads of the second metatarsals. In addition, markers were placed over the right and left middle deltoid muscles. The alignment of these shoulder markers with the pelvic markers allowed measurement of the trunk flexion angle during the VJ and LSU.

Depending on the order of testing, kinematic and kinetic data were collected as each subject performed the VJ and LSU. The single-leg VJ was demonstrated, and the subject performed 3 practice trials prior to data collection. The subject took one step onto the force platform, flexed the lower extremity, performed a maximal VJ, and landed on the force platform with the same lower extremity (Fig. 1). Data were collected for 3 trials and averaged. The subject used his or her natural jumping technique, with no restrictions on the countermovement or use of the arms. At the completion of the 3 VJs, the subject indicated his or her level of pain during the test by marking a spot with a pencil on a visual analog scale (VAS), which consisted of a 10-cm line with "no pain" written on the far left side of the line and "worst pain imaginable" written on the far right side.[31]

The LSU was performed with an 18-cm-high step mounted on the force platform with preloading.[32] The procedure was demonstrated, and the subject performed

Table 2.
Internal Knee Extension Moment of Each Lower Extremity (LE) During Each Activity (in Newton-meters per Kilogram) for Subjects With Anterior Cruciate Ligament (ACL) Reconstructions and Matched Comparison Subjects

	Subjects With ACL Reconstructions (n=20)						Comparison Subjects (n=20)					
	Involved LE			Uninvolved LE			Matched LE			Unmatched LE		
Activity	$\overline{X}$	SD	Range	$\overline{X}$	SD	Range	$\overline{X}$	SD	Range	$\overline{X}$	SD	Range
Vertical jump take-off	1.05[a]	0.50	0.18–2.26	1.41	0.31	1.22–2.06	1.43	0.28	0.92–1.94	1.55	0.34	1.00–2.19
Vertical jump landing	1.30[a]	0.59	0.25–2.30	2.09	0.49	1.27–3.37	1.91	0.45	1.28–3.03	1.89	0.45	1.33–3.36
Lateral step-up	0.98[a]	0.30	0.43–1.51	1.28	0.27	0.81–1.91	1.33	0.26	0.81–1.82	1.30	0.18	0.97–1.64

[a] Significantly different from the uninvolved extremity and both extremities of the matched subjects for each activity ($P<.001$).

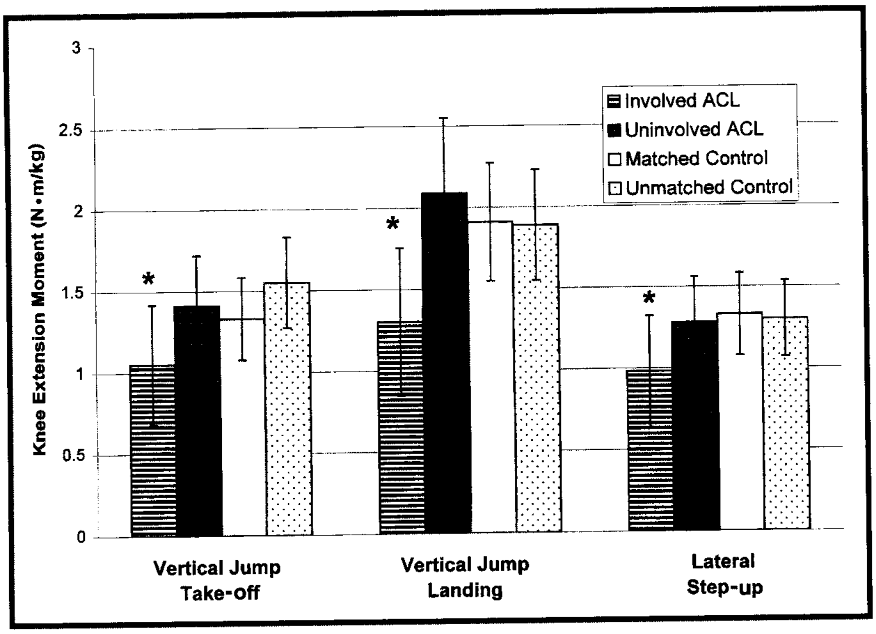

Figure 3.
Knee extension moments during the lateral step-up, vertical jump take-off, and vertical jump landing for each extremity in the group with anterior cruciate ligament (ACL) reconstructions and the comparison group. Asterisk (*) indicates significantly different from the uninvolved and matched extremities in each activity.

each comparison subject was designated as the same side as the involved extremity of the matched subject in the experimental group. The initial alpha level was set at .05 and was divided by the number of dependent variables (2) to control for Type I error. The Tukey Honestly Significant Difference (HSD) test was used in the *post hoc* analyses.

The Pearson product-moment correlation was used to assess the relationship between knee extension moment and maximum trunk flexion angle and between knee extension moment and pain during the VJ and LSU. These relationships were studied separately in the ACL-reconstructed extremity, the uninvolved extremity, and the matched extremity. The alpha level was again set at .05.

Results

Descriptive statistics for subject characteristics are presented in Table 1. The ANOVA for knee extension moment revealed a group × extremity × activity interaction ($F=10.72$; $df=2,76$; $P<.001$). This finding indicated that the difference between the involved and uninvolved extremities for each of the 3 activities was different for the experimental and comparison groups. The Tukey HSD *post hoc* analysis revealed that the knee extension moment of the involved lower extremity of the subjects with ACL reconstructions was less than that of their uninvolved lower extremity and the matched lower extremities of the comparison subjects for each of the 3 activities (Tab. 2 and Fig. 3). There was no difference between the uninvolved lower extremity of the subjects with ACL reconstructions and the matched lower extremity of the comparison subjects and no difference between the lower extremities of the comparison subjects.

The ANOVA for summated extension moments revealed a group × extremity × activity interaction ($F=11.04$; $df=2,76$; $P<.001$). *Post hoc* analysis showed that, for the VJ landing, the summated extensor moment of the involved lower extremity of the subjects with ACL reconstructions was less than that of their uninvolved lower extremity and the matched lower extremities of the comparison subjects (Tab. 3 and Fig. 4). All other pair-wise comparisons showed no difference between the groups or extremities.

No correlations were found between trunk flexion angle and knee extension moment ($r=-.23$ to .13, $P>.05$) or VAS pain score and knee extension moment ($r=-.13$ to

Table 3.
Summated Internal Knee Extension Moment of Each Lower Extremity (LE) During Each Activity (in Newton-meters per Kilogram) for Subjects With Anterior Cruciate Ligament (ACL) Reconstructions and Matched Comparison Subjects

	Subjects With ACL Reconstructions (n=20)						Comparison Subjects (n=20)					
	Involved LE			Uninvolved LE			Matched LE			Unmatched LE		
Activity	$\bar{X}$	SD	Range	$\bar{X}$	SD	Range	$\bar{X}$	SD	Range	$\bar{X}$	SD	Range
Vertical jump take-off	5.92	1.48	2.37–8.25	5.69	1.19	3.67–8.19	6.15	1.01	4.25–8.08	6.33	1.03	4.83–7.63
Vertical jump landing	4.69[a]	1.18	2.55–6.44	5.66	1.06	3.40–7.45	5.50	0.92	3.88–7.09	5.55	0.70	4.03–6.72
Lateral step-up	2.66	0.36	1.90–3.50	2.77	0.29	2.20–3.23	2.72	0.32	2.24–3.31	2.89	0.27	2.53–3.55

[a] Significantly different from the uninvolved extremity and both extremities of the matched subjects in the vertical jump landing ($P<.001$).

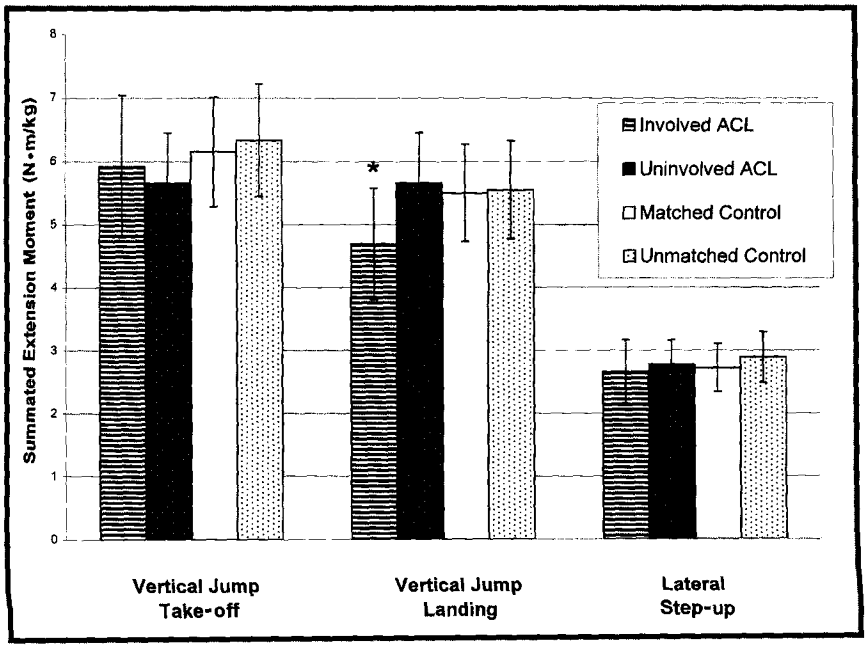

Figure 4.
Summated extension moments during the lateral step-up, vertical jump take-off, and vertical jump landing for each extremity in the group with anterior cruciate ligament (ACL) reconstructions and the comparison group. Asterisk (*) indicates different from the uninvolved, matched, and unmatched extremities during the vertical jump landing.

−.34, $P>.05$) for each extremity under the 3 activity conditions.

Discussion

To our knowledge, there is only one study[24] in which lower-extremity kinetics or kinematics were examined during functional activities in people who have had ACL reconstructions. Thus, it is difficult to compare our findings with those of researchers who used other measures. Our finding of a decreased knee extension moment during all 3 tested activities would seem to be due to quadriceps femoris muscle weakness. For example, the mean knee extension moment during VJ landing was 1.30 N·m/kg for subjects with ACL reconstructions compared with 2.09 N·m/kg for the comparison subjects. However, with lower-extremity weight-bearing activities, the neuromuscular system may also recruit the hip extensors and the soleus muscle to assist knee extension. Therefore, the decrease in knee extension moment that we found may not have been due solely to quadriceps femoris muscle weakness, but may have been due to the use of other muscle groups besides the quadriceps femoris muscle to extend the knee (ie, the hip extensors and/or soleus muscle). Based on the origin and insertion, the gluteus maximus muscle can exert a posteriorly directed force on the proximal femur to extend the knee while the pelvis and foot are stabilized. Similarly, with the foot fixed on the floor, the soleus muscle can exert a posteriorly directed force on the proximal tibia to produce knee extension. In our opinion, these muscle groups generated larger moments at the hip and ankle to make up for the knee extensor moment deficit. The concept that the hip and ankle extensor moments can compensate for knee extensor moment deficits is supported by the fact that the VJ take-off and LSU summated extensor moments for the involved lower extremity of the subjects with ACL reconstructions were equal to those of their uninvolved lower extremities and the matched lower extremities of the comparison subjects in spite of a smaller knee extensor moment.

The decrease in knee extension moment could also be due to pain or forward trunk leaning during the LSU and VJ. The amount of leaning can increase or decrease the tendency of the center of mass to flex the knee. A corresponding change in the moment generated by the quadriceps femoris muscle is needed to counteract this tendency of the body mass to flex the knee.[25] Theoretically, as an individual flexes at the trunk, the tendency of the external moment arm of the center of mass (perpen-

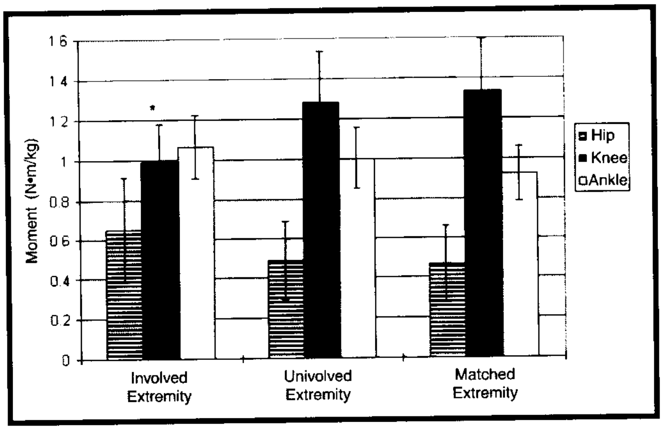

Figure 5.
Hip, knee, and ankle extension moments during the lateral step-up. Asterisk (*) indicates knee extensor moment of involved extremity was different from knee extensor moments of the uninvolved and matched extremities ($P<.05$).

dicular distance between the center of mass and the knee joint center) to flex the knee decreases. This decrease presumably results in a smaller internal knee extension moment to overcome the tendency of the center of mass to flex the knee. However, this hypothesis was not supported by our data, as there was no relationship between knee extension moment and trunk flexion angle. Although pain may be thought to decrease the knee extension moment, there was no correlation between level of pain on the VAS and knee extension moment. Therefore, our findings appear to support the concept that the decrease in knee extensor moment is due either to quadriceps femoris muscle weakness or to some alteration of central neuromuscular programming where hip or ankle extensors may be recruited.

The summated extensor moment (hip + knee + ankle extension moments) was originally investigated by Winter[34] and was in reference to the stance phase of gait. He found that the summated extensor moment was consistent across a group of uninjured and injured subjects during walking. When a deficit existed in one joint, Winter found that other lower-extremity joints would compensate and increase their extension moments to maintain the summated extension moment throughout the lower extremity and thus prevent the limb from collapsing during the stance phase of gait. This finding is consistent with our findings of symmetrical summated extensor moments in the presence of knee extensor moment deficits in the VJ take-off and LSU.

In the VJ landing, however, the involved lower extremity of the subjects with ACL reconstructions had a smaller extensor moment that their uninvolved lower extremity or the matched lower extremities of the comparison subjects. Of the 3 activities, we would theorize that the VJ landing would be the most likely to cause a "limb collapse" and thus necessitate the maintenance of a symmetrical summated extensor moment. However, it is apparent that the hip and ankle did not compensate enough to maintain this summated extensor moment. Perhaps the rapid and forceful contractions required by the lower-extremity muscle groups during the landing was too great a demand for the neuromuscular system to respond with a normal summated extensor moment.

A clinical implication of our findings is that the neuromuscular system can recruit hip or ankle muscle groups during lower-extremity weight-bearing exercise and testing. Clinicians, therefore, should be aware that, when prescribing the lateral step-up or similar exercises, the hip and ankle may contribute to the knee extensor moment and the contribution of the knee extensors may be reduced. Figure 5 provides a interesting comparison of the hip, knee, and ankle extension moments during the LSU. The knee extension moment appeared to be the predominant extensor moment in the uninvolved lower extremity of the subjects with ACL reconstructions and the matched lower extremities of the comparison subjects, whereas the ankle extension moment appeared to be the predominant extension moment in the involved lower extremity of the subjects with ACL reconstructions.

We conducted a 2-factor within-subjects ANOVA (joint versus extremity) and a 1-factor between-subjects ANOVA (group) with Tukey HSD *post hoc* tests to examine differences in joint extensor moments in the extremities of both groups while performing the LSU. In the matched extremity of the comparison subjects and the uninvolved extremity of the subjects with ACL reconstructions, the knee extensor moment was greater than both the hip and ankle extensor moments ($F=17.6$; $df=2,76$; $P<.001$). In the involved extremity of the subjects with ACL reconstructions, however, there was no difference between the knee and ankle extensor moments. For example, in the involved extremity of the subjects with ACL reconstructions, the knee extension moment of 0.98 N·m/kg was no different from the ankle extension moment at 1.06 N·m/kg. In the uninvolved extremity, the knee extension moment at 1.28 N·m/kg was greater than both the hip extension moment (0.49 N·m/kg) and the ankle extension moment (1.00 N·m/kg). Thus, we believe the ankle musculature was contributing just as much as the knee to the total extensor moment to complete the LSU. In the uninvolved extremity of the subjects with ACL reconstructions and the matched extremities of the comparison subjects, the quadriceps femoris muscle generated the predominant extensor moment. We believe the sole reliance on unsupervised lower-extremity weight-bearing strengthening exercises may not provide an adequate stimulus for quadriceps femoris muscle force gains in patients following autograft patellar tendon ACL reconstruction.

The VJ test requires a coordinated effort of all lower-extremity joints. Although the VJ test and the similar one-legged hop test are used to measure performance following knee injury or surgery, they are, in our view, measures of total lower-extremity performance and not just measures of knee performance. The satisfactory performance of a one-legged hop test, in our opinion, does not indicate a normal a normal knee extensor mechanism.

Future Research

The results of our study showed that the hip and/or ankle extension moments apparently increase in an effort to make up for a deficit in the knee extension moment. How long these compensations exist and whether these compensations adversely affect an individual's overall performance or subject the individual to an increased risk for injury is unclear. Future areas for study should include measuring the duration of these compensations and tracking patients or athletes to determine whether the performance or injury rate of individuals decreases as a result of compensations. A similar kinetic analysis comparing patients having a patellar tendon autograft with those having an allograft or hamstring muscle graft procedure may assist the surgeon in deciding which graft would favor optimal lower-extremity function. Finally, research to determine the best rehabilitation program to restore normal synchronization and proportionate contribution of lower-extremity muscle groups during functional activity will ultimately benefit the patient attempting to return to normal lower-extremity function following ACL reconstruction.

Conclusion

This study provided support that the hip and ankle extensors are capable of compensating for a knee extension moment deficit in the involved extremity of patients after ACL reconstruction during an LSU exercise and VJ take-off. Clinicians whose patients perform these activities for quadriceps femoris muscle rehabilitation should be aware these compensations may occur and take adequate measures to ensure appropriate quadriceps femoris muscle recruitment. When using the single-legged VJ test for patients after ACL reconstruction, we contend that clinicians should be aware that this test is a measure of total lower-extremity performance. A normal test result may be an indication of adequate compensation by the hip and ankle musculature and may not necessarily indicate normal knee extension force. During VJ landing, compensation by the hip and ankle musculature did not occur in the ACL-reconstructed extremity and resulted in a deficit in the summated extension moment. This deficit in the summated extensor moment may decrease the musculoskeletal system's ability to attenuate shock during landing and expose the musculoskeletal system to greater stress. Further research is needed to determine the importance of this deficit and to examine rehabilitation programs designed to restore the summated extension moment.

References

1 Johnson RJ. The anterior cruciate ligament problem. *Clin Orthop.* 1983;172:14–18.

2 Fu FH, Schulte KR. Anterior cruciate ligament surgery 1996: state of the art? *Clin Orthop.* 1996;325:19–24.

3 Liljedahl SO, Lindvall N, Wetterfors J. Early diagnosis and treatment of acute ruptures of the anterior cruciate ligament: a clinical and arthrographic study of forty-eight cases. *J Bone Joint Surg Am.* 1965;47:1503–1513.

4 Jacobsen K. Osteoarthosis following insufficiency of the cruciate ligaments in man: a clinical study. *Acta Orthop Scand.* 1977;48:520–526.

5 Fetto JF, Marshall JL. The natural history and diagnosis of anterior cruciate ligament insufficiency. *Clin Orthop.* 1980;147:29–38.

6 Noyes FR, Matthews DS, Mooar PA, Grood ES. The symptomatic anterior cruciate deficient-knee, part II: the results of rehabilitation, activity modification, and counseling on functional disability. *J Bone Joint Surg Am.* 1983;65:163–174.

7 Feagin JA Jr, Curl WW. Isolated tear of the anterior cruciate ligament: 5-year follow-up study. *Am J Sports Med.* 1976;4:95–100.

8 Rubinstein RA Jr, Shelbourne KD, VanMeter CD, et al. Isolated autogenous bone-patellar tendon-bone graft site morbidity. *Am J Sports Med.* 1994;22:324–327.

9 Lephart SM, Kocher MS, Harner CD, Fu FH. Quadriceps strength and functional capacity after anterior cruciate ligament reconstruction: patellar tendon autograft versus allograft. *Am J Sports Med.* 1993;21:738–743.

10 Shelbourne KD, Wilckens JH. Current concepts in anterior cruciate ligament rehabilitation. *Orthop Rev.* 1990;19:957–964.

11 McCarroll JR. Fracture of the patella during a golf swing following reconstruction of the anterior cruciate ligament: a case report. *Am J Sports Med.* 1983;11:26–27.

12 Bonamo JJ, Krinick RM, Sporn AA. Rupture of the patellar ligament after use of its central third for anterior cruciate ligament reconstruction: a report of two cases. *J Bone Joint Surg Am.* 1984;66:1294–1297.

13 Langan P, Fontanetta AP. Rupture of the patellar tendon after use of its central third. *Orthop Rev.* 1987;16:317–321.

14 Paulos LE, Rosenberg TD, Drawbert J, et al. Infrapatellar contracture syndrome: an unrecognized cause of knee stiffness with patella entrapment and patella infera. *Am J Sports Med.* 1987;15:331–341.

15 Graf B, Uhr F. Complications of intra-articular anterior cruciate ligament reconstruction. *Clin Sports Med.* 1988;7:835–848.

16 Yasuda K, Ohkoshi Y, Tanabe Y, Kaneda K. Muscle weakness after anterior cruciate ligament reconstruction using the patellar and quadriceps tendons. *Bull Hosp Jt Dis Orthop Inst.* 1991;51:175–185.

17 Rosenberg TD, Franklin JL, Baldwin GN, Nelson KA. Extensor mechanism function after patellar tendon graft harvest for anterior cruciate ligament reconstruction. *Am J Sports Med.* 1992;20:519–526.

18 Yasuda K, Ohkoshi Y, Tanabe Y, Kaneda K. Quantitative evaluation of knee instability and muscle strength after anterior cruciate ligament

reconstruction using patellar and quadriceps tendon. *Am J Sports Med.* 1992;20:471–475.

19 Shino K, Inoue M, Horibe S, et al. Reconstruction of the anterior cruciate ligament using allogeneic tendon: long-term follow-up. *Am J Sports Med.* 1990;18:457–465.

20 Barber SD, Noyes FR, Mangine RE, et al. Quantitative assessment of functional limitations in normal and anterior cruciate ligament-deficient knees. *Clin Orthop.* 1990;255:204–214.

21 Noyes FR, Barber SD, Mangine RE. Abnormal lower limb symmetry determined by function hop test after anterior cruciate ligament rupture. *Am J Sports Med.* 1991;19:513–518.

22 Wilk KE, Romaniello WT, Soscia SM, et al. The relationship between subjective knee scores, isokinetic testing, and functional testing in the ACL-reconstructed knee. *J Orthop Sports Phys Ther.* 1994;20:60–73.

23 Berchuck M, Andriacchi TP, Bach BR, Reider B. Gait adaptations by patients who have a deficient anterior cruciate ligament. *J Bone Joint Surg Am.* 1990;72:871–877.

24 Kowalk DL, Duncan JA, McCue FC III, Vaughan CL. Anterior cruciate ligament reconstruction and joint dynamics during stair climbing. *Med Sci Sports Exerc.* 1997;29:1406–1413.

25 Berger RA, Elbaum LH, Hodge WA. Advantages in total body performance of unicompartmental knee replacement over total knee replacement. *Orthopedic Transactions.* 1990;14:406.

26 Andriacchi TP, Mikosz RP. Musculoskeletal dynamics, locomotion, and clinical application. In: Mow VC, ed. *Basic Orthopedic Biomechanics.* New York, NY: Raven Press; 1991:51–92.

27 Irrgang JJ. Modern trends in anterior cruciate ligament rehabilitation: nonoperative and postoperative management. *Clin Sports Med.* 1993;12:797–813.

28 Spencer JD, Hayes KC, Alexander IJ. Knee joint effusion and quadriceps reflex inhibition in man. *Arch Phys Med Rehabil.* 1984;65:171–177.

29 Tegner Y, Lysholm J. Rating systems in the evaluation of knee ligament injuries. *Clin Orthop.* 1985;198:43–49.

30 *Vicon Motion Analysis System Reference Manual.* Oxford, England: Oxford Metrics; 1995.

31 Price DD, McGrath PA, Rafii A, Buckingham B. The validation of visual analogue scales as ratio scale measures for chronic and experimental pain. *Pain.* 1983;17:45–56.

32 Besser MAP, Kowalk DL, Vaughan CL. Mounting and calibration of stairs on piezoelectric force platforms. *Gait & Posture.* 1993;1:231–235.

33 Ernst GP, Kawaguchi J, Saliba E. The effect of patellar taping on knee kinetics of patients with patellofemoral pain syndrome. *J Orthop Sports Phys Ther.* 1999;29:661–667.

34 Winter DA. Overall principle of lower limb support during stance phase of gait. *J Biomech.* 1980;13:923–927.