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Comparison of Clinical and Dynamic Knee Function in Patients with Anterior Cruciate Ligament Deficiency

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Background: Whether passive measures of isokinetic muscle strength deficits and knee laxity are related to the dynamic function of the anterior cruciate ligament-deficient knee remains unclear.

Hypotheses: Arthrometer measurements are not predictive of peak external knee flexion moment (net quadriceps muscle moment), isokinetic quadriceps muscle strength correlates with peak external knee flexion moment (net quadriceps muscle moment), and isokinetic hamstring muscle strength correlates with peak external knee extension moment (net flexor muscle moment).

Study Design: Cross-sectional study.

Methods: Gait analysis was used to assess dynamic function during walking, jogging, and stair climbing in 44 subjects with unilateral anterior cruciate ligament deficiency and 44 control subjects. Passive knee laxity and isokinetic quadriceps and hamstring muscle strength were also measured.

Results: Arthrometer measurements did not correlate with peak external flexion or extension moments in any of the activities tested or with isokinetic quadriceps or hamstring muscle strength. Test subjects also had a significantly reduced peak external flexion moment during all three jogging activities and stair climbing compared with the control subjects and this was correlated with significantly reduced quadriceps muscle strength.

Conclusions: Absolute knee laxity difference did not correlate with dynamic knee function as assessed by gait analysis and should not be used as a sole predictor for the outcome of treatment. Patients with greater than normal strength in the anterior cruciate ligament-deficient limb performed low- and high-stress activities in a more normal fashion than those with normal or less-than-normal strength.

The ACL is one of the most commonly injured structures of the knee.[9] A complete rupture of the ACL may lead to significant posttraumatic laxity, functional disability, and degenerative arthritis of the knee.[10,12,14,17,20] Noyes et al.[20] first popularized the "rule of thirds," where one-third of patients with an ACL-deficient knee will compensate adequately and be able to pursue recreational activities, one-third will compensate but give up a significant number of activities, and one-third will perform poorly and require reconstructive surgery. However, determining which patients are able to compensate and how they compensate is not entirely clear.

Often during the clinical examination of a patient, the degree of joint laxity[6,9,20] and isokinetic quadriceps and hamstring muscle strength deficits[13,22,23] are used to predict functional outcome and treatment of patients with ACL ruptures. Numerous studies have provided information on changes in gait patterns, muscle activity, knee stability, and strength associated with ACL deficiency.[2,8,16,18,24] These studies have reported how adaptive changes in the knee motion and moments in the sagittal plane could be beneficial to the patient by helping him or

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her stabilize the knee joint through muscular activity, thereby preventing symptoms of laxity during daily and athletic activities.[2,8] However, whether passive measures of knee laxity or isokinetic muscle strength are related to the dynamic function of patients with ACL deficiency remains unclear. Therefore, the purpose of this study was to determine whether passive measures of knee laxity and isokinetic muscle strength are related to changes in patterns of locomotion as quantified by the knee motion and moments during walking, jogging, and stair activities.

The following hypotheses were tested:

- Knee arthrometry measurements are not predictive of the peak external knee flexion moment (net quadriceps muscle moment).
- Isokinetic quadriceps muscle strength is correlated with the peak external knee flexion moment (net quadriceps muscle moment).
- Isokinetic hamstring muscle strength is correlated with the peak external knee extension moment (net flexor muscle moment).

MATERIALS AND METHODS

Subjects

Forty-four subjects who had sustained a unilateral ACL injury and were symptomatic volunteered for this study. Fourteen of these subjects were seen clinically with an acute injury and had an interval from injury to testing of less than 3 months, whereas 30 subjects had chronic ACL deficiency and had an interval from injury to testing of greater than 3 months. The average interval from injury to testing for all subjects was 21 ± 31 months (range, 1 to 124). Subjects with significant knee effusions were not included in this study because of their inability to perform the gait and strength tests. The subjects were recruited from the practices of two experienced orthopaedic surgeons (CAB and BRB). The selection criteria included patients with a complete ACL rupture, no other ligament injury, and no greater than 50% loss of the medial and lateral menisci. In 36 of the subjects, arthroscopic examination confirmed complete ACL tears and meniscal loss of no greater than 50%. The remaining eight subjects were clinically examined by the orthopaedic surgeon and had a complete ACL tear diagnosed on the basis of history and positive results of the Lachman, anterior drawer, and pivot shift tests. Furthermore, these eight subjects had no detectable meniscal damage as assessed by clinical examination. Meniscal injury was assessed by history and physical examination parameters, including knee motion, joint line tenderness, knee swelling, and the presence of mechanical symptoms. At the time of the gait evaluation, 33 of the 44 subjects were scheduled for ACL reconstruction because of symptomatic instability or unacceptable functional limitations.

Forty-four uninjured control subjects (25 men, 19 women) also volunteered for this study. These subjects had no history of neuromusculoskeletal injury or disease. The age, height, weight, and sex distribution of the control subjects were comparable with that of the test subjects (25 men, 19 women) ($P > 0.464$). The left or right side of the control subject was matched to the injured side of the test subject. Demographic data of the subjects are shown in Table 1. Institutional Review Board approval for this study and informed consent were obtained for all subjects.

Subjective Questionnaire

All subjects in the ACL-deficient group completed a detailed questionnaire that included questions on the mechanism of injury, treatment since the injury, preinjury and postinjury activity level, and function during activities of daily living. Subjects reported their ability to return to preinjury level of sports activity and their ability to run and cut. Episodes of locking, buckling, or swelling with activities of daily living were also reported.

Clinical Examination

Physical examination, which was conducted on both lower extremities, included examination for patellofemoral crepitation, joint swelling and tenderness, range of motion, and leg-length discrepancy. Range of motion was tested with the patient in the supine position. Atrophy of the thigh and leg was assessed by measuring the difference in circumferences between the injured and uninjured limbs. Thigh circumference was measured 20 cm proximal to the proximal pole of the patella with the knee in extension. Examination for anteroposterior laxity was performed with the Lachman, pivot shift, and anterior drawer tests.

Measurements of passive knee laxity were made with the KT-2000 arthrometer (MEDmetric Corporation, San Diego, California), a commonly used instrument to quantify anteroposterior laxity of the knee. In this study, analyses of passive knee laxity were performed at the manual maximum test difference because this test revealed the greatest displacement difference between the injured and uninjured knees.

Isokinetic Strength Testing

Kin-Com (Kin-Com Corporation, Chattanooga, Tennessee) or Cybex II (Lumex Inc., Ronkonkoma, New York)

TABLE 1
Demographic Data for the Test and Control Subjects

Group	Sex[a]	Side[a]	Age[b] (years)	Height[b] (meters)	Weight[b] (Newtons)
ACL-deficient	25 M, 19 F	27 L, 17 R	29 ± 9	1.72 ± 0.09	727 ± 145
Control	25 M, 19 F	27 L, 17 R	30 ± 9	1.72 ± 0.11	718 ± 162

[a] M, male; F, female; L, left; R, right.
[b] Mean ± SD.

dynamometers were used to measure torque generation of the quadriceps and the hamstring muscle groups as a measure of extension and flexion strength, respectively. The Kin-Com and Cybex dynamometers were used to test each subject in both groups for three to four trials of flexion and extension at speeds of 60, 180, and 240 deg/sec. The 60 deg/sec data were analyzed for all subjects. With the Kin-Com dynamometer, separate trials were conducted for flexion and extension, and with the Cybex dynamometer, a single continuous trial was conducted. Thirty-six subjects (29 test subjects and 7 control subjects) were tested on the Kin-Com dynamometer from July 1995 to November 1996, and 52 subjects (15 test subjects and 37 control subjects) were tested on the Cybex dynamometer from November 1996 to July 1998.

To determine whether the strength values measured on the two machines were comparable, we tested 20 control subjects on both machines. Although the strength values measured by the two systems were significantly different, the Cybex and Kin-Com dynamometer data correlated significantly for both the quadriceps muscles ($R = 0.87$; $P < 0.001$) and hamstring muscles ($R = 0.82$; $P < 0.001$) at 60 deg/sec. The percent error between the two machines was 10% for quadriceps muscle strength and 16% for hamstring muscle strength at 60 deg/sec. For the present analysis, regression equations were established to convert Kin-Com results to Cybex results for subjects tested on the Kin-Com dynamometer.

Gait Analysis

Subjects were tested by using an optoelectronic camera system and a multicomponent force plate, which measured the ground reaction force.[5] Reflective markers were placed externally on the skin at five bony landmarks: superior and lateral-most aspect of the iliac crest, lateral aspect of the greater trochanter, lateral joint line of the knee, lateral malleolus, and the head of the fifth metatarsal. Limb motion was measured by using the optoelectronic camera system and was determined by tracking the spatial position of markers placed on the lower extremity. The geometric centers of the hip, knee, and ankle were determined from the marker positions and anthropometric measurements. Inverse dynamics were used to calculate the external moments and intersegmental joint forces by first modeling the limb as a collection of rigid segments (slender rods) representing the thigh, shank, and foot. Each segment was assumed to be symmetric about its longitudinal axes, with a negligible angular velocity and acceleration about the longitudinal axis of the segment (link model). The three-dimensional external moments at each joint center were calculated from the ground reaction force, inertial properties, and the three-dimensional position of the joint centers. All moments were transformed into the local coordinate system of each joint, which for the knee was aligned with the shank.[4] External moments were normalized to the subject's body weight multiplied by his or her height (% Bw × Ht).

This study focused on the peak external knee flexion and extension moments during all activities. The reason for this is that the peak external knee flexion moment is balanced by a net quadriceps muscle moment, while the peak external extension moment is balanced by a net knee flexor muscle moment. Electromyographic studies have shown that during walking, the quadriceps muscles are active during the middle part of stance (midstance) and the hamstring muscles are active at the beginning of stance.[21] Therefore, the peak external flexion moment (net quadriceps muscle moment) and the peak external extension moment (net flexor muscle moment) at these time periods were analyzed because they reflect quadriceps and hamstring muscle function, respectively.

All subjects performed at least six trials of level walking at self-selected speeds of slow, normal, and fast and at least two trials of jogging, jog-stop, and jog-cut on each side.[3] Jog-stop was performed by having the subject jog to a specific location (on the force plate) in a straight line and come to a sudden stop on the limb being tested. Jog-cut was performed by having the subject jog up to a specific location (on the force plate) and cut at 90° off the limb being tested. Subjects also ascended and descended stairs on a two-step staircase.[1] Seven of the 44 subjects in the ACL-deficient group were not comfortable performing some or all of the jogging activities and thus were not tested during these activities. Six of the 44 test subjects were not tested during the stair activities because during the time when these subjects were tested, the protocol in the gait laboratory did not include ascending and descending stairs. Therefore, a subgroup of 38 subjects in the ACL-deficient group was tested during the stair activities. All 44 control subjects were tested during all activities.

Statistical Analysis

Dynamic function and isokinetic strength differences between the ACL-deficient group and the control group were identified with the use of independent Student's *t*-tests. Only the injured knee of test subjects was analyzed for this study. To test the relationship between passive knee laxity (manual maximum KT-2000 arthrometer difference), isokinetic strength (peak quadriceps and hamstring muscle torque), and dynamic function (peak external sagittal plane knee moments), we used multivariate regression models and Pearson correlation coefficients. A significance level of $\alpha < 0.05$ was used for all analyses.

To minimize the effect of walking and jogging speed on the associated moments, we chose a representative trial at about the same speed for walking trials for both the ACL-deficient and control groups (1.13 ± 0.20 m/sec, $P = 0.454$) and similarly for the jogging trials (2.60 ± 0.39 m/sec, $P = 0.143$).

RESULTS

Although most subjects in the ACL-deficient group had a manual maximum difference (injured − uninjured) of greater than 3 mm (average, 6.5 ± 3.0) (Fig. 1), knee arthrometer measurements did not correlate with the peak external flexion (net quadriceps) or extension (net knee flexor) moments during any of the activities tested

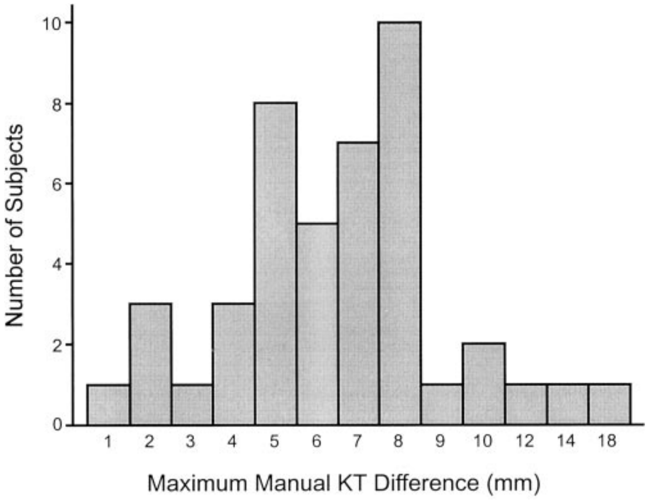

Figure 1. Histogram of the side-to-side difference (injured – uninjured) at manual maximum testing for the ACL-deficient group (mean ± SD, 6.5 ± 3.0 mm).

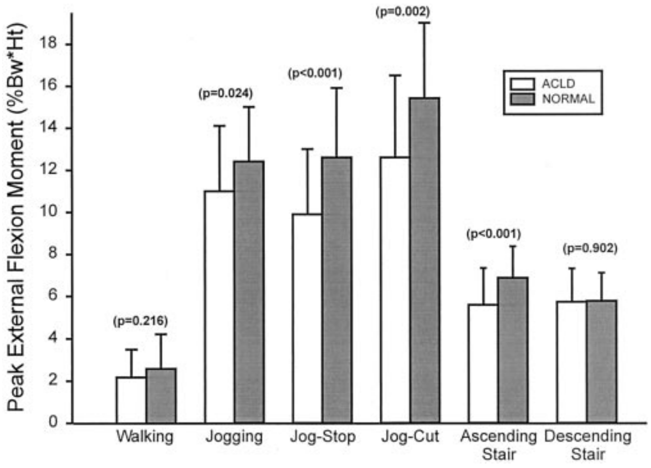

Figure 2. Peak external flexion moments (mean ± SD) for all of the activities tested. ACLD, ACL-deficient group; normal, control group.

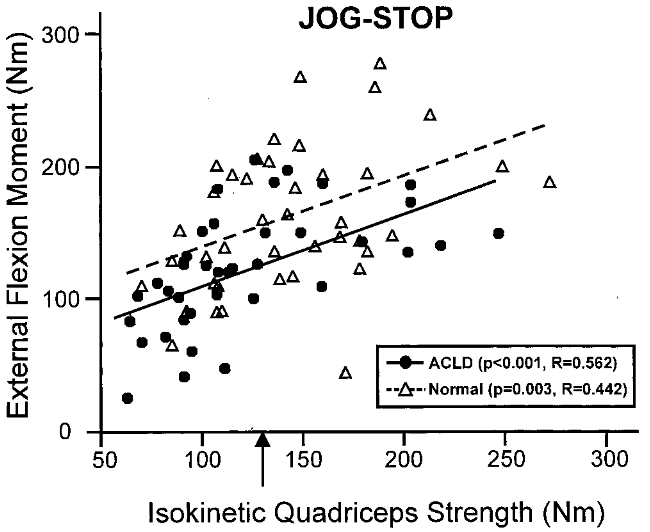

Figure 3. Relationship between isokinetic quadriceps muscle strength and external knee flexion moment during jog-stop for the ACL-deficient (ACLD) and control (normal) groups. The average strength when both groups are combined was 130 N·m, which is represented by the arrow.

($P > 0.130$). All of the test subjects with a KT-2000 arthrometer difference of 3 mm or less had had their ACL rupture confirmed by arthroscopic examination. The subjects without arthroscopic confirmation of their ACL ruptures had a difference of at least 5.5 mm (range, 5.5 to 12). To further examine whether knee laxity predicted dynamic function, we compared the five subjects who had a laxity difference of 3 mm or less and the six subjects with a difference of 9 mm or more. By using a repeated-measures analysis of variance, we determined that the peak external flexion and extension moments for the subjects with the least knee laxity were not significantly different from those of the subjects with the most knee laxity ($P > 0.186$).

The ACL-deficient group had significantly less isokinetic quadriceps muscle strength (9.6% ± 2.6% Bw × Ht) than the control group (11.3% ± 2.4% Bw × Ht) ($P < 0.001$), and this strength difference was related to a significant decrease in the peak external flexion (net quadriceps) moment during the more strenuous activities. The quadriceps muscle strength for the ACL-deficient group was 84% that of the control group. During jogging, jog-stop, jog-cut, and ascending stair activities, the peak external flexion moment for the ACL-deficient group was also significantly less than that for the control group (Fig. 2). The isokinetic quadriceps muscle strength was significantly correlated with the peak external flexion moment during all three of the jogging activities and the ascending stair activity ($P < 0.003$) in both the ACL-deficient and control groups. However, for a given quadriceps muscle strength, the ACL-deficient group produced a lower external knee flexion (net quadriceps) moment than the control group (Fig. 3). For instance, at the average quadriceps strength of both groups (130 ± 45 N·m), the predicted external flexion moment was significantly less in the ACL-deficient group than in the control group ($P = 0.001$). In contrast to the jogging activities, the walking and descending stair activities involved no significant correlation between quadriceps muscle strength and the external flexion moment in either group. Moreover, during the walking and descending stairs activities, the external flexion moment was not significantly different between the ACL-deficient and control groups.

During walking, the ACL-deficient group had a significantly reduced external knee extension (net knee flexor) moment compared with the control group during the late part of the stance phase, and this extension moment was significantly correlated with the knee angle at late stance ($P < 0.001$, R = 0.850). Furthermore, the ACL-deficient group had a significantly greater knee angle at late stance compared with the control group (Fig. 4). The peak external extension moment was not significantly different between the two groups during the other activities of jogging and stair climbing ($P > 0.573$) (Fig. 5).

The isokinetic hamstring muscle strength for the ACL-deficient group was not significantly different (4.7% ± 1.8% Bw × Ht) from that of the control group (5.3% ± 1.6% Bw × Ht) ($P = 0.133$). In both the ACL-deficient and control groups, hamstring muscle strength was not correlated with the peak external extension moment for all activities tested. Furthermore, passive measures of knee laxity did not correlate with quadriceps ($P = 0.754$) or hamstring ($P = 0.948$) muscle strength.

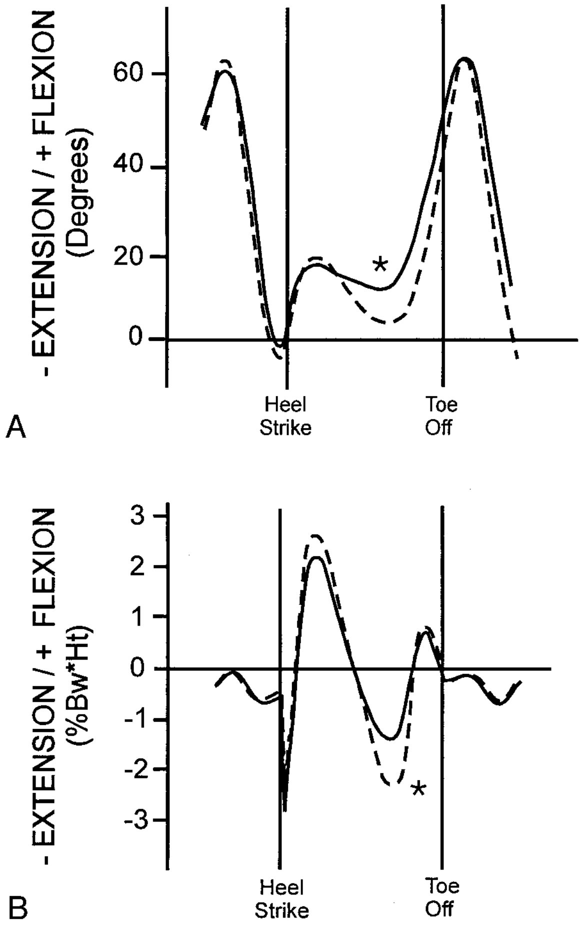

Figure 4. Comparison of sagittal plane knee motion (A) and sagittal plane knee moment (B) between the ACL-deficient group (solid line) and the control group (dashed line) during walking. The peaks represent the average of each group. The asterisk indicates significant difference ($P < 0.05$) between the two groups.

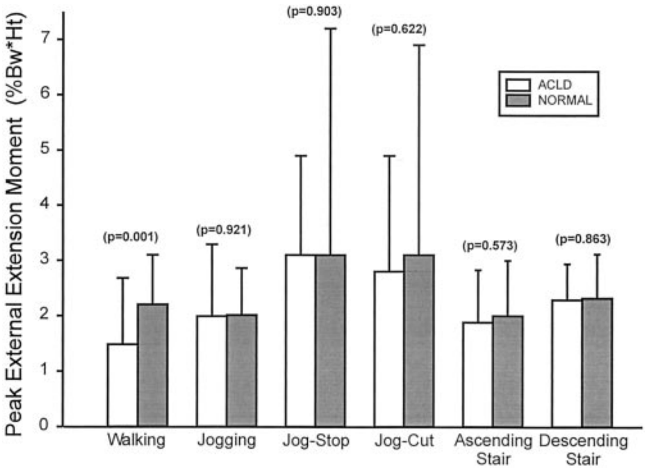

Figure 5. Peak external extension moments (mean ± SD) at heelstrike for all jogging activities and descending stairs. Peak external extension moment at terminal stance for walking and ascending stairs. ACLD, ACL-deficient group; normal, control group.

DISCUSSION

Many studies have examined the relationship between passive knee laxity/isokinetic strength and functional performance tests, such as measured time and distance for various hop tests and shuttle runs.[7,11,15,18] However, few studies have evaluated the relationship between laxity/isokinetic strength and the dynamic knee function (kinematics or kinetics) during activities of daily living in patients with an ACL-deficient knee. Although passive measures of knee laxity are useful in diagnosing an ACL rupture, their usefulness in predicting dynamic knee function is not quite clear. In this study we found that passive measures of knee laxity were not indicative of dynamic knee function during walking, jogging, or stair activities. These findings are consistent with the results of other studies that have shown no relationship between knee laxity and functional performance test or functional outcome scores (that is, Lysholm knee score).[7,10,15,25]

Furthermore, the ACL-deficient group in this study had significantly less isokinetic quadriceps muscle strength than the control group and, during the more strenuous activities, this was related to reductions in the dynamic quadriceps knee function, as assessed by the external flexion (net quadriceps muscle) moment. These correlations between quadriceps muscle strength and dynamic quadriceps muscle function during the more strenuous activities are consistent with results of other studies showing correlations between quadriceps muscle strength deficits and performance during functional tests.[15,19] Although the quadriceps muscle strength significantly correlated with the peak external flexion moment during the more strenuous activities in both the ACL-deficient and control groups, the subjects in the ACL-deficient group required greater quadriceps muscle strength to produce an external flexion moment comparable with that of the control group. The lack of a correlation between quadriceps muscle strength and the external flexion moment during the less stressful activity of walking could be due to the fact that walking places lower demands on the quadriceps muscle as compared with the other activities.

In a previous study from our laboratory, the presence of a "quadriceps avoidance gait" was reported in some patients with an ACL-deficient knee.[8] This pattern is most likely to emerge among subjects who are at least 7.5 years from their injury date.[27] In the present study, most of our subjects were within 2.5 years of their injury, which may account for the absence of this adaptation in our subjects during their walking test. The peak external flexion moment in the present group of subjects with an ACL-deficient knee was only slightly, but not significantly, decreased during walking. The significantly decreased peak flexion moment during the more strenuous jogging activity is consistent with results of other studies.[2,8]

The isokinetic hamstring muscle strength of the ACL-deficient group was not significantly different from that of the control group. In the literature, conflicting findings have been reported with respect to hamstring muscle strength.[13,15,18,19,26] In the present study, the isokinetic hamstring muscle strength also did not significantly correlate with the peak external extension moment in the ACL-deficient group.

A limitation of the current study is the fact that more of the subjects in the ACL-deficient group were tested on the Kin-Com dynamometer and more of the control subjects were tested on the Cybex dynamometer. It is therefore possible that the quadriceps muscle strength deficit or lack of hamstring muscle deficit in the ACL-deficient group relative to the control group may be a result of this. However, numerous studies by other investigators have reported significant quadriceps muscle strength deficits in patients with ACL deficiency.[13,15,18,19,26] Moreover, the strength deficit in the current study was highly significant ($P < 0.001$). Thus, we believe that the quadriceps muscle strength deficit in the ACL-deficient group was not a result of the testing protocol. Less certain is whether the lack of a difference in the hamstring muscle strength between the groups was a result of the testing protocol. The ACL-deficient group tended to have weaker knee flexors, although this difference was not significant. Conflicting findings have been reported with respect to hamstring muscle strength.[13,15,18,19,26] When the Kin-Com and Cybex dynamometer data were analyzed separately, the relationships between the strength, external moments, and KT-2000 arthrometer data were similar to those reported here.

In this study, patients were recruited from the clinical practices of two senior surgeons, and all of the patients had received a clinical diagnosis of ACL deficiency. Therefore, these findings are only applicable to symptomatic patients seeking care. The inclusion criteria were also limited to subjects with a complete ACL rupture, no other ligament injury, a loss of no greater than 50% of the medial and lateral menisci, and no significant effusion. No inclusion or exclusion criteria were applied relative to activity level, sports involvement, or other factors. The study group, therefore, represents those patients typically seen in an orthopaedic practice. In patients with effusion, the quadriceps muscle strength and its relationship to dynamic function may be different. Additional adaptations may be present in patients with effusion or more extensive meniscal injuries.

The choice of method of treatment for patients with ACL injuries is based on several factors. These include patient age, activity level, degree of laxity, presence of associated meniscal and ligament injuries, and patient compliance and motivation. Treatment options include nonoperative rehabilitation, activity modification, or surgical reconstruction. In this study, passive measures of laxity (KT-2000 arthrometry) were not predictive of dynamic knee function and should not be used as a factor in the election of various treatment options. Isokinetic strength, however, appears to be an important factor in the nonoperative treatment of patients with ACL injuries. Although the majority of patients were noted to have decreased quadriceps muscle strength, those patients with more normal quadriceps muscle strength displayed more normal dynamic knee function. Thus, restoring and maintaining appropriate quadriceps muscle strength after ACL injuries may be beneficial.

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