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Dynamic Function After Anterior Cruciate Ligament Reconstruction with Autologous Patellar Tendon

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ABSTRACT

The purpose of this study was to dynamically assess the functional outcome of patients who had undergone successful anterior cruciate ligament reconstruction using an autologous patellar tendon technique and to determine whether their dynamic knee function was related to quadriceps and hamstring muscle strength. The knee kinematics and kinetics of 22 subjects who had undergone anterior cruciate ligament reconstruction (mean age, 27 ± 11 years) and of 22 age- and sex-matched healthy control subjects were determined during various dynamic activities using a computerized motion analysis and force plate system. The differences in the sagittal plane angles and external moments between the two groups during light (walking), moderate (climbing and descending stairs), and higher-demand (jogging, jog and cut, jog and stop) activities were related to isokinetic strength measurements. Although patients who are asymptomatic and functioning well after anterior cruciate ligament reconstruction can perform normally in light activities, higher-demand activities reveal persistent functional adaptations that require further study.

Injury to the ACL leads to knee instability and functional adaptations. Although many ACL-deficient patients display little or no visible impairment (primarily because of activity modification), previous studies have shown that patients with ACL deficiencies walk and perform more stressful activities differently than do uninjured subjects, with most of the differences occurring in the sagittal plane angles and moments.[5,9,11,15,20] For example, Devita et al.[9] and Kadaba et al.[11] reported that ACL-deficient subjects walk with decreased knee flexion and decreased external knee extension (internal net knee flexor) moments in a terminal stance.

The purpose of our study was to determine whether functional adaptations during gait and other low- and high-demand activities were present in patients with an ACL bone-patellar tendon reconstruction and, if so, whether they were related to strength. More specifically, we examined how the sagittal plane joint angles and external moments during walking, stair-climbing, and jogging activities differed between healthy subjects and patients with a reconstructed ACL and whether those differences related to isokinetic quadriceps and hamstring muscle strength.

MATERIALS AND METHODS

Twenty-two subjects (mean age, 27 ± 11 years) who underwent an autogenous patellar tendon reconstruction for ACL deficiency were tested and compared with a group of 22 uninjured control subjects. The ACL-reconstructed group consisted of 13 men and 9 women. Patients in the ACL-reconstructed group underwent surgery at an average of 8 months (range, 1 to 24) after injury and were examined at a mean follow-up of 22 ± 12 months. Excluded from the study were those patients who had meniscal damage in which more than 25% of the meniscus was removed, posterior cruciate or collateral ligament injury, articular surface injury, symptomatic anterior knee pain, or objective instability at latest follow-up examination (positive pivot shift test results, positive Lachman

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test results, or arthrometer side-to-side differences of more than 3 mm). Postoperative rehabilitation included immediate weightbearing and full range of motion. Patients were allowed to begin jogging at 3 months and allowed unrestricted activity at 6 months. Subjects in the control group (13 men, 9 women; mean age, 29 ± 8 years) had no history of musculoskeletal abnormalities or lesions and had not undergone any musculoskeletal operative procedures. The ACL-reconstructed group and control subjects were not matched for sports or activity level, but subjects in the control group reported no sports or activity restrictions. The age, height, and weight were not significantly different between the control and ACL-reconstructed groups ($P > 0.40$), and an equal distribution of men and women were in each group. In the ACL-reconstructed group, the right side was affected in 8 of the subjects and the left side in the other 14 subjects. Therefore, 8 right sides and 14 left sides were chosen as the affected side for analysis of subjects in the control group.

All subjects in the ACL-reconstructed group completed a subjective questionnaire and underwent physical examination with parameters that included thigh circumference, mechanical axis, medial-lateral stability at 30°, and results of the Lachman and pivot shift tests. Isokinetic strength testing was performed using a Cybex Model X (Cybex International, Inc., Medway, Massachusetts) or a Kincom 500H (Chattanooga Group, Hixson, Tennessee) at 60, 180, and 240 deg/sec. Strength data at 60 deg/sec were collected from all subjects, and data at 180 and 240 deg/sec were collected on all but one subject who had an ACL reconstruction. A KT-1000 knee arthrometer (MEDmetric Corp., San Diego, California) was used to determine side-to-side differences at maximum manual levels (40 pounds) on all ACL-reconstructed subjects.

Subjects in the ACL-reconstructed and control groups underwent gait analysis using a multicamera optoelectronic digitizer (Computerized Functional Testing Corporation, Chicago, Illinois, or Selspot Innovision System, Warren, Michigan), a multicomponent force plate (Bertec Corporation, Columbus, Ohio), and a computer. The geometric centers of the hip, knee, and ankle were determined by using markers placed over skeletal prominences.[1] Inverse dynamics were used to resolve the external moments about each joint in the flexion-extension, abduction-adduction, and internal-external rotation axes. All moments were normalized to percentage of body weight times height (%Bw × Ht) to allow for intersubject comparisons.[1]

The moments reported are the external moments and include the effects of ground-reaction force, limb segment weight, and limb segment inertia. External moments are balanced by internal moments generated by muscles, soft tissues, and joint contact forces on the basis of mechanical equilibrium. Thus, an external knee flexion moment is balanced by a net internal knee extensor moment or net quadriceps muscle activity. Similarly, an external knee extension moment is balanced by a net knee flexor moment.

Each subject was tested in low-demand (walking, stair-climbing) and higher-demand activities (jogging, cutting, jog and stop) (Fig. 1). Three subjects in the ACL-reconstructed group were not tested ascending stairs, and four subjects in the ACL-reconstructed group were not tested descending stairs. These subjects were tested before stair-climbing was included as part of the testing protocol. Jog and stop data for one control subject were lost during computer processing. During walking, subjects were asked to walk at self-selected speeds of slow, normal, and fast, and results of at least six trials on each side were collected. During jogging, subjects jogged at their own self-selected speed, and results of at least two trials on each side were collected. Walking speed has previously been shown to influence the magnitude of the sagittal plane moments[1]; thus, results of a representative walking trial at about the same speed for everyone was chosen for analysis. The average walking speed of the subjects in the trials analyzed was not significantly different between the two groups ($P = 0.677$) and averaged 1.18 ± 0.16 m/sec in the ACL-reconstructed group and 1.16 ± 0.16 m/sec in the control group. A jogging trial at about the same speed for everyone was also chosen for analysis. Similarly, the average jogging speed of the trial analyzed was not significantly different between the two groups ($P = 0.096$) and averaged 2.79 ± 0.39 m/sec in the ACL-reconstructed group and 2.58 ± 0.42 m/sec in the control group.

In the primary analysis *t*-tests were used to identify significant differences between the ACL-reconstructed and control groups in isokinetic strength, sagittal plane

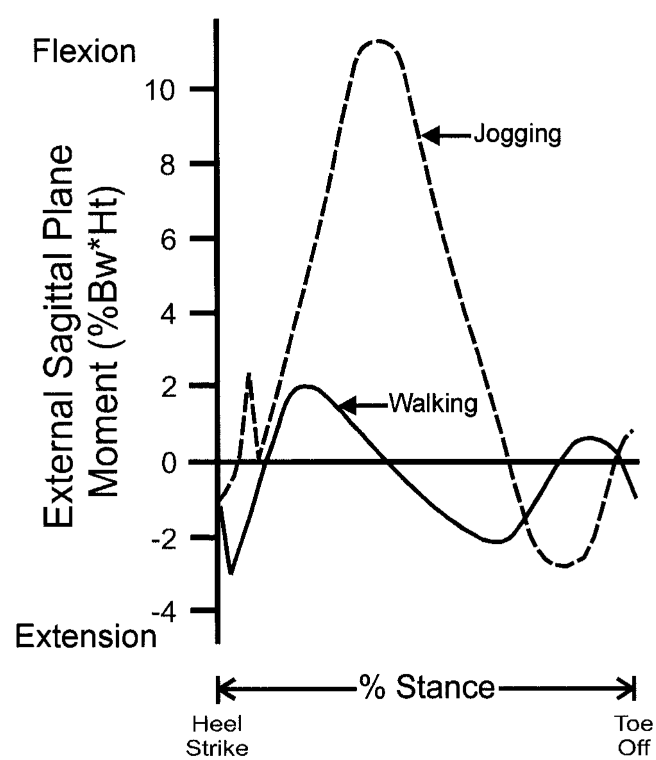

Figure 1. The external flexion moment during jogging is much greater than that during walking, as shown above by the typical sagittal plane moment pattern for these activities for an ACL-reconstructed subject.

angles, and peak external moments. When walking speed or jogging speed was still significantly correlated with the sagittal plane peak moments, significant differences between the groups were tested for using an analysis of variance in which speed was included as a covariate. Significant correlations between the sagittal plane moments and the measured isokinetic strength were tested for using Pearson correlation coefficients. A significance level of $\alpha < 0.05$ was used throughout.

RESULTS

All 22 patients in the ACL-reconstructed group were satisfied with the outcome of surgery. Of the 22 patients, 15 resumed their preinjury level of sports participation, 5 described mild limitations, and 2 had not resumed sports for reasons unassociated with the function of their knee. Six of 22 patients described occasional activity-related swelling, and 3 of 22 described occasional use of over-the-counter medications for pain and swelling.

Physical examination revealed that 19 of 22 patients in the ACL-reconstructed group regained symmetric knee extension, and 3 patients had a flexion contracture of less than 5°. Twelve of 22 patients had thigh atrophy ranging from 0.1 to 2 cm. All patients regained objective stability, with negative Lachman and pivot shift test results. The KT-1000 arthrometer knee testing results were available for 17 of 22 patients and revealed side-to-side differences of 3 mm or less.

The isokinetic quadriceps muscle strength, in newton-meters, tended to be slightly lower on the ACL-reconstructed side as compared with that of the control subjects, but only when tested at 60 deg/sec, and this difference was not statistically significant ($P = 0.144$) (Fig. 2). At the two faster test speeds the quadriceps muscle strength was not significantly different from that of the control subjects ($P > 0.397$). When the quadriceps muscle strength was normalized to the height and weight of each subject, the normalized isokinetic quadriceps muscle strength on the ACL-reconstructed side was significantly lower than that of the control subjects at 60 deg/sec ($P = 0.031$). This effect was not observed at the faster test speeds ($P > 0.125$). The side-to-side deficit between the affected and unaffected sides (ratio of quadriceps muscle strength on the affected side to that of the unaffected side) of the ACL-reconstructed group (0.97 ± 0.16 at 60 deg/sec) was not significantly different from that of the control group (1.04 ± 0.18 at 60 deg/sec) at any of the three speeds ($P > 0.174$).

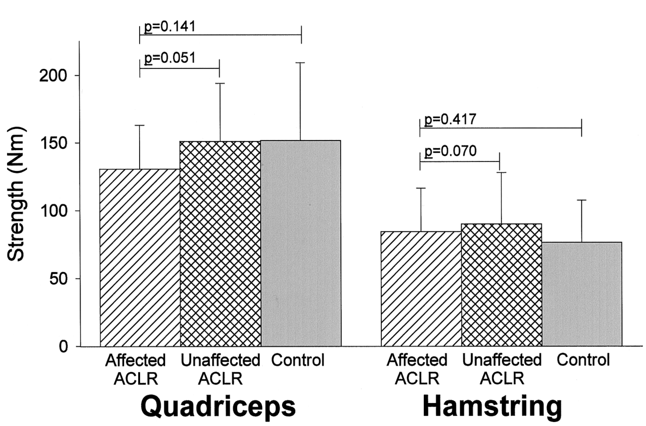

Figure 2. Isokinetic strength (in newton-meters) tested at 60 deg/sec on the affected side of the ACL-reconstructed group (ACLR) was not significantly different from that of the control group.

The isokinetic hamstring muscle strength as measured in newton-meters or when normalized to weight and height was not significantly different between the ACL-reconstructed and control groups at any of the test speeds ($P > 0.267$, $P > 0.179$, respectively). Moreover, the side-to-side deficit ratios of the ACL-reconstructed group (0.92 ± 0.33 at 60 deg/sec) were not significantly different from those of the control group (1.08 ± 0.30 at 60 deg/sec) at any of the three speeds ($P > 0.131$).

When testing the correlations in newton-meters between the isokinetic quadriceps muscle strength to the peak external flexion moment and between the isokinetic hamstring muscle strength to the peak external extension moment, the strongest correlations were almost always found in the 60 deg/sec strength data. For this reason, correlation coefficients for the strength data at 60 deg/sec were primarily chosen to be presented in this article.

Only slight reductions in the peak external flexion moment (net quadriceps moment) with level walking were evident in the ACL-reconstructed group. Only two of the ACL-reconstructed subjects and one of the control subjects walked with a quadriceps avoidance gait (the persistence of an external extension moment throughout most of the stance). Even over the narrow range of speeds selected for this analysis, the peak midstance external flexion moment was still significantly correlated with walking speed (ACL-reconstructed group, $r^2 = 0.201$, $P = 0.036$; control group, $r^2 = 0.342$, $P = 0.004$). For this reason, speed was included as a covariate when testing whether the peak external midstance flexion moment was significantly different between the two groups. The peak external midstance flexion moment of the ACL-reconstructed group was less than that of the normal group ($P = 0.051$) after accounting for the significant effect of walking speed ($P = 0.001$). Even though the ACL-reconstructed group had a lower peak external flexion moment during midstance, the midstance knee flexion angle was not significantly different between the two groups ($P = 0.636$). The terminal knee extension angle during stance was significantly greater in the ACL-reconstructed group ($8° \pm 4°$) as compared with the control group ($5° \pm 4°$) ($P = 0.020$). When compared with the control group, the ACL-reconstructed group revealed no significant differences in the peak external flexion moment when ascending and descending stairs ($P = 0.081$, $P = 0.246$, respectively).

The decrease in the peak external flexion moment (net quadriceps moment) in the ACL-reconstructed group became more pronounced during the more demanding activities such as jogging and jog and cut (Fig. 3). During jog-and-cut maneuvers, the peak external flexion moment of the ACL-reconstructed group (13.3 ± 3.9 %Bw × Ht) was significantly less than that of the control group (16.1 ± 4.2 % Bw × Ht) ($P = 0.024$). Similarly, during jogging the peak external flexion moment of the ACL-reconstructed group was significantly less than that of the control group ($P = 0.005$) after accounting for the significant effect of speed ($P = 0.002$). The peak external flexion moment during jog-and-stop maneuvers was not significantly different from that in the control group ($P = 0.175$).

The peak external flexion moment, which was significantly less during jogging in the ACL-reconstructed group than in the control group, was significantly correlated with the quadriceps muscle strength at 60 deg/sec in both the ACL-reconstructed ($r^2 = 0.464$, $P < 0.001$) and control groups ($r^2 = 0.289$, $P = 0.010$) (Fig. 4). In both groups the peak external flexion moment was also significantly correlated with the quadriceps muscle strength data at the faster speeds ($P < 0.020$). Therefore, the subjects in the ACL-reconstructed group with the weakest quadriceps muscles had the greatest reductions in the peak flexion moment during jogging. In contrast, while the peak midstance knee flexion moment in level walking was slightly reduced in the ACL-reconstructed group, it was not significantly correlated with quadriceps muscle strength in either group ($P > 0.133$). Similarly, although the peak flexion moment during jog and cut was significantly less than normal in the ACL-reconstructed group compared with the control group, this moment was not significantly correlated with quadriceps muscle strength at any speed in the ACL-reconstructed group ($P > 0.113$). However, it was significantly correlated with quadriceps muscle strength in the control group at all speeds ($r^2 = 0.308$ to 0.391, $P < 0.008$).

The peak external extension moment (net knee flexor moment) was not significantly different between the two groups during walking ($P = 0.356$), ascending stairs ($P = 0.545$), jogging ($P = 0.100$), and jog and cut ($P = 0.125$). The peak external extension moment (net knee flexor moment) in the ACL-reconstructed group was significantly greater than in the control group ($P = 0.026$) during descending stairs and tended to be increased during jog and stop ($P = 0.053$).

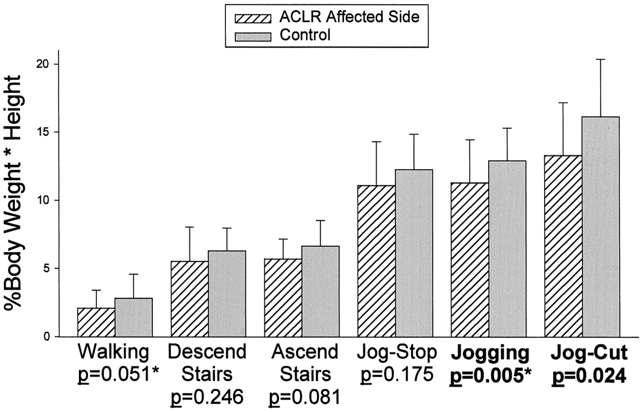

Figure 3. The peak external flexion moment of the ACL-reconstructed group (ACLR) was significantly less than that of the control group during higher-demand activities (jog and cut, $P = 0.024$; jogging, $P = 0.005$). The asterisk indicates a significant difference when speed was included as a covariate in the analysis.

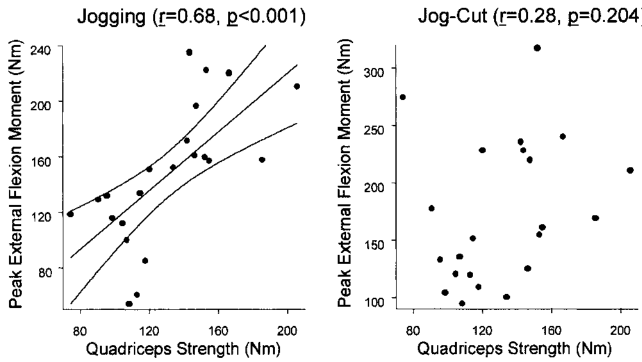

Figure 4. Although the peak external flexion moment of the ACL-reconstructed group was significantly less than that of the control group during both jogging and jog and cut, the peak moment was correlated with strength only during jogging, and not during jog and cut.

The isokinetic hamstring muscle strength was only significantly correlated with the peak external extension moment during jog and stop in the ACL-reconstructed group ($r^2 = 0.383$, $P = 0.002$ at 60 deg/sec) and not in the control group ($P = 0.116$ at 60 deg/sec). Therefore, the increased peak external extension moment during jog and stop in the ACL-reconstructed group was more pronounced among those with increased hamstring muscle strength. In contrast, the increased external extension moment in the ACL-reconstructed group during descending stairs was not related to their isokinetic hamstring muscle strength ($P > 0.126$ for all speeds).

DISCUSSION

Berchuck et al.[5] reported that ACL-deficient subjects walked with a decreased midstance knee flexion angle and a quadriceps avoidance gait, and Wexler et al.[20] reported a decreased external knee flexion moment. The quadriceps avoidance gait was suggested to be a protective mechanism against excessive quadriceps muscle-induced anterior translation of the tibia with the knee near full extension.[5] Both Birac et al.[6] and Wexler et al.[20] found that the quadriceps avoidance gait or a decreased external flexion moment, respectively, were related to time since injury. Wojtys and Huston[21] have also noted time-dependent alterations in muscular response to knee subluxations in both the injured and uninvolved extremity in ACL-deficient subjects. The consensus among many of these authors is that functional adaptations in ACL-deficient patients are, in part, time-dependent and involve some form of neuromuscular retraining.[5,8,9,11,13,18,21]

Advancements in surgical technique have led to a rise in the number of patients undergoing ACL reconstruction.

Arthroscopic reconstruction using a patellar tendon technique, one of the most common methods, results in a successful reconstruction in 91% to 93% of patients.[2,7] Arciero et al.[2] reported that patients regained 98.5% thigh girth and 97% quadriceps muscle strength at an average follow-up of 31 months. Bach et al.[4] used subjective testing, static parameters (KT-1000 arthrometer, pivot shift phenomenon), and clinical tests of function (such as single-legged hop and shuttle run) in 104 consecutive patients who had undergone arthroscopically assisted ACL reconstruction. They noted that 97% of the patients were subjectively satisfied, 91% had negative pivot shift test results, and 89% had functional deficits of less than 10%.

Despite high levels of reported clinical success, concern has been raised regarding quadriceps muscle function in patients with an ACL bone-patellar tendon reconstruction.[2,3,5,10,12,14,16] Moreover, a significant reduction in the external flexion moment (net quadriceps moment) during walking has been reported among 10 patients 8 to 12 months after patellar tendon autograft ACL reconstruction.[19] Decreases in the angular impulse and work at the hip and knee have been noted among 8 ACL-reconstructed patients after completion of rehabilitation (average 6 months after surgery).[8] Tibone and Antich[17] found that although 9 of 11 ACL-reconstructed patients (average 2 years after surgery) had an improved ability to perform a cutting maneuver as assessed by force plate data, significant differences from the uninvolved side persisted, and only 5 of the 11 patients were able to return to their preinjury level of activity. The patients in that study all had a patellar tendon autograft coupled with a lateral extraarticular tenodesis, and 7 of the 11 underwent partial medial or lateral meniscectomy.

The results of our study clearly show that functional adaptations during more demanding athletic activities were present among the subjects who had a well-functioning ACL reconstruction. Moreover, these adaptations occurred even though only marginal quadriceps muscle strength loss was seen in the ACL-reconstructed group as compared with the control group. This study is the first to examine functional adaptations during walking and other more demanding activities in a uniform group of patients with well-functioning ACL reconstructions without significant meniscal loss or arthritic deterioration and to relate the adaptations to isokinetic strength measurements.

Although significant reductions in the midstance external flexion moment (level walking) before and after ACL reconstruction have been reported,[5,19,20] only slight reductions in the peak external flexion moment were evident in the ACL-reconstructed group.

Despite excellent clinical results, significant decreases in the peak external flexion moment were noted with higher-demand activities, including jogging and jog and cut. When patients were jogging, the decrease in the peak external flexion moment was correlated with strength. Those patients with relatively weaker quadriceps muscles displayed more dramatic reductions in the external flexion moments than did those with more normal strength. These data reinforce the value of ensuring complete quadriceps muscle rehabilitation after ACL reconstruction. These data are also consistent with the findings of Patel,[15] who noted that greater isokinetic quadriceps muscle strength was predictive of normal dynamic function during higher-demand activities.

However, the same effect was not noted with jog-and-cut maneuvers of the ACL-reconstructed subjects in our study. Although the peak external flexion moment was significantly reduced from normal, it did not correlate with quadriceps muscle strength. Other factors exclusive of strength, including patient apprehension, decreased proprioception, or microinstability, may in part be the cause of the patients' decreased ability to generate a normal peak external-flexion moment.

In summary, patients with well-functioning patellar tendon ACL reconstructions and minimal decreases in quadriceps muscle strength as compared with healthy subjects displayed virtually no abnormality with low-demand activities, including walking and stair climbing. However, with higher-demand activities, persistent adaptations were present and may be minimized in part with improved muscle strength.

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