Functional adaptations in knee kinematics and kinetics during level walking in 30 patients with unilateral anterior cruciate ligament deficiency and 30 healthy control subjects were studied. To examine the impact of time after injury on the functional adaptations, patients were placed into three time interval groups: early, intermediate, and chronic. The patients with anterior cruciate ligament deficiency had significantly decreased external knee flexion moments (balanced by net quadriceps contraction) and significantly increased external knee extension moments (balanced by net knee flexors contraction) as compared with the control subjects. As time after the injury increased, changes in the sagittal plane knee moments were more pronounced. A significant linear relationship (positive correlation) was found between the midstance knee flexion moment and the corresponding knee flexion angle. The patients with anterior cruciate deficiency had a greater knee flexion angle when generating a comparable midstance knee flexion moment as compared to the control subjects. The identification of gait adaptations over time provides additional information on the natural history of anterior cruciate ligament deficiency and may have implications regarding conservative rehabilitation, evaluation of outcomes, progression of meniscal injury, and the development of degenerative arthritis of the knee.

Functional Gait Adaptations in Patients With Anterior Cruciate Ligament Deficiency Over Time

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The loss of anterior cruciate ligament function has been shown to lead to increased mechanical instability of the knee. Berchuck et al described the absence of a net external knee flexion moment at midstance during level walking in patients with anterior cruciate ligament deficiency. This functional adaptation was referred to as a quadriceps avoidance gait pattern. The quadriceps avoidance gait could be a protective mechanism against excessive anterior translation of the proximal tibia. A reduction in quadriceps contraction when the knee is near full extension would help diminish anterior translation of the proximal tibia. However, Berchuck et al did not relate this functional adaptation to the time after the initial injury. The development of functional adaptations during time may have implications affecting the probability of having subsequent degenerative changes develop in the knee.
knee and in providing an assessment of the clinical success of patients' compensatory measures.

Natural history studies of anterior cruciate ligament deficiency have provided insight into the fate of the injured patient who does not undergo reconstruction of the ligament. A consensus exists in the literature as to the outcome of nonsurgical treatment for the young, active individual with anterior cruciate ligament deficiency: progressive and predictable knee dysfunction manifested by repeated episodes of instability, an increased potential for meniscal and chondral injury, and an increased incidence of osteoarthritis in the knee. Hawkins et al.\(^7\) showed that only 14% of patients with anterior cruciate ligament deficiency who went through conservative rehabilitation were able to return to their preinjury level of activity. Other studies have shown that roughly 2/3 of patients with chronic anterior cruciate ligament deficiency adapt their lifestyles by discontinuing or reducing athletic activity. Daniel et al.\(^11\) found that the hours per year of participation in strenuous sports activity before injury to the anterior cruciate ligament was the most important single predictor of the need for reconstruction of the ligament. Hawkins et al.\(^17\) showed that only 14% of patients with anterior cruciate ligament deficiency who went through conservative rehabilitation were able to return to their preinjury level of activity. Other studies have shown that roughly 2/3 of patients with chronic anterior cruciate ligament deficiency adapt their lifestyles by discontinuing or reducing athletic activity.\(^17,23,24\)

Instability, associated injuries, and osteoarthritis of the knee often are reported as sequelae of the anterior cruciate ligament deficiency. Some patients with anterior cruciate ligament deficiency never may have repeated episodes of knee instability develop. The incidence of buckling or giving way, however, has ranged from as high as 90% to as low as 25%.\(^8,14,17–19,21\) Approximately half of all injuries that result in a cruciate ligament rupture also result in a concomitant meniscal injury.\(^11,12,22\) Moreover, as time after injury increases, so does the rate of injury to the menisci. Daniel et al.\(^11\) showed that 20% of their patients with unstable knees who did not undergo acute reconstruction of the anterior cruciate ligament went on to late surgical treatment of meniscal injuries. Daniel and Dameron\(^20\) found only eight patients with intact menisci in a 10 year followup of 53 patients with anterior cruciate ligament deficiency. The loss of anterior cruciate ligament function changes the normal femoral and tibial gliding and rolling and also may increase the susceptibility of the meniscus to injury. Chondral injuries and degenerative changes develop at an increased rate after anterior cruciate ligament tears. The development of chondral changes in chronic anterior cruciate ligament deficiency has a reported incidence of 50%\(^12\) whereas the progression to degenerative osteoarthritis as reported in long term followup studies ranges from 50% to 92%.\(^14,15,21,22,25\)

Observation of the clinical manifestations of pathologic ambulation provides unique insights into the study of musculoskeletal disease.\(^1\) Gait analysis provides accurate and objective data about the mechanics and function of the anterior cruciate ligament deficient knee that may lead to future improvements in the methods of treatment.\(^2–28\) The sequelae of anterior cruciate ligament deficiency along with identification of the gait adaptations associated with anterior cruciate ligament deficiency leads to the question of how patients adapt to their initial injury over time. Whether all patients develop gait pattern changes, during what time interval changes develop, and to what significance are questions that have not yet been answered. Answering these and other questions related to anterior cruciate ligament deficiency can aid the practitioner in defining treatment goals and can provide an objective means for evaluating therapeutic interventions, whether nonoperative or surgical.

The purpose of this study was to test the hypothesis that mechanisms of functional adaptation in patients with anterior cruciate ligament deficiency change during time. The incidence of gait pattern changes during level walking are documented in patients with unreconstructed, anterior cruciate ligament deficient knees at specific time intervals after their initial injury to delineate how
patients compensate for loss of anterior cruciate ligament function during time.

MATERIALS AND METHODS

Thirty patients with unreconstructed, unilateral anterior cruciate ligament deficiency were included in this study. The diagnosis of complete rupture of the anterior cruciate ligament was confirmed at arthroscopic surgery or at later reconstruction in all patients. Patients with meniscal damage in which more than 25% of the meniscus was removed, and patients with collateral ligament or posterior cruciate ligament injury as determined by examination with the patient under general anesthesia or arthroscopic findings, were excluded from the study. None of the patients had functionally limiting pain at the time of gait analysis. The patients were divided into three groups, determined by the interval of time between their index injury to the anterior cruciate ligament and the gait analysis. The groups were 0 to 2.5 years, 2.5 to 7.5 years, and greater than 7.5 years representing early, intermediate, and chronic time intervals. There were 15 patients in the early group, nine patients in the intermediate group, and six patients in the chronic group. The longest interval between injury and gait analysis was 18 years.

The anterior cruciate ligament deficiency group included 24 men and six women with a mean age of 30 ± 7 years, mean height of 1.8 ± 0.1 m, and mean weight of 81 ± 13 kg. Complete clinical examination (knee alignment, thigh circumference, and laxity testing) at the time of gait analysis was performed on 27 of the patients (Table 1). Examination of the remaining three patients was incomplete and therefore was not included. Physical examination was not used in the selection criteria for this study, but rather to provide clinical information which characterizes this particular study population.

The opposite, noninjured extremity was not used as a control because adaptive patterns of gait have been described previously in the contralateral side of patients with anterior cruciate ligament deficiency. Thus, a control group of 30 healthy volunteers matched for age and gender was selected. The mean age of these healthy subjects was 29 ± 7 years; the mean height, 1.7 ± 0.1 m; and the mean weight, 69 ± 13 kg. None of the control subjects had any musculoskeletal pathology of their lower extremities, and none had undergone any prior operative musculoskeletal procedures. All clinical tests for knee stability were normal for the control subjects.

The study and control groups underwent identical protocols in the gait analysis laboratory. The subjects were asked to walk at three self selected speeds of slow, normal, and fast on a 10-m walkway. At least six trials per side were collected and a representative trial at approximately 1.1 m per second was chosen for analysis. The representative trial was compared with the other trials of the subject to ensure that the magnitudes and patterns of the kinematics and kinetics did not contain any artifacts associated with a miss step or the contralateral limb striking the force plate.

The instrumentation for gait analysis included a two-camera optoelectronic digitizer (Selspot—Innovation System, Warren, MI, or CFTC, Chicago, IL), a multicomponent force plate (Bertec Corp, Columbus, OH, or Kistler Corp, Amherst, Massachusetts).
NY), and a computer. Markers were placed at the iliac crest, greater trochanter, lateral joint line of the knee, lateral malleolus, base of the fifth metatarsal, and the calcaneus (Selspot only). The geometric centers of the hip, knee, and ankle were determined from the marker positions. The knee center was located at the midpoint of a line between the peripheral margins of the medial and lateral plateau at the level of the joint surface. The three-dimensional kinematics of the joint centers then were computed using a link model in which the inertial properties of each segment were lumped at its mass center. The three-dimensional kinetics of the joint centers then were computed using a link model in which the inertial properties of each segment were lumped at its mass center. External moments about each joint were transformed to a local coordinate system that moved with each limb segment. The three-dimensional components thus were resolved along the flexion and extension, abduction and adduction, and internal and external rotation axes. At the knee the local axes followed the motion of the shank. All of the moments were expressed as a percentage of the subject’s weight times height so that comparisons could be made between the subjects.

The moments that are reported are external moments and include the effect of the ground reaction force, limb segment weight, and limb segment inertia. On the basis of mechanical equilibrium, internal moments of equal magnitude are generated which must balance these measured external moments. The internal moments are generated by muscles, soft tissues, and joint contact forces. Thus an external flexion moment would be balanced by net quadriceps muscle activity and an external extension moment would be balanced by net knee flexor activity. The external moment, however, reflects the net effect of the quadriceps and the knee flexor muscle performance because cocontraction of these muscles is possible.

The sagittal plane knee moments normally have a biphasic pattern (Fig 1). The external knee moment changes from an extension moment just after heelstrike (initial knee extension moment), to a flexion moment at the end of loading response or the beginning of midstance (early midstance knee moment), to an extension moment during terminal stance (terminal stance knee moment), to a flexion moment during preswing (preswing knee flexion moment). The analysis of the quadriceps avoidance gait pattern was based on the early midstance knee moment (Fig 1). In the case of anterior cruciate ligament deficiency, there is often a net avoidance (quadriceps avoidance gait) or reduction of this net external flexion moment. The quadriceps avoidance gait pattern thus is defined by the presence of a net external knee extension moment at early midstance rather than an external flexion moment as typically seen among healthy subjects.

A statistical analysis of the knee kinematics and kinetics of the patients with anterior cruciate ligament deficiency and the control subjects was performed. Attention was directed toward changes between the specified time intervals. Differences between the average values for the anterior cruciate ligament deficient groups at the different time intervals and the control group were analyzed with an analysis of variance (ANOVA) and Bonferroni correction for multiple group comparisons. Testing was done for significant differences between the slopes and intercepts of a linear regression model based on the anterior cruciate deficient subjects and between the slopes and intercepts of a linear regression model based on the control subjects. A significance level of $\alpha < .05$ was used for all statistical analyses.

**RESULTS**

The anterior cruciate ligament deficient group had a significantly decreased midstance knee
The midstance knee flexion moment was reduced in each time interval group when compared with the midstance knee flexion moment of the control subjects ($p < .001$). Seventeen (57%) of the patients with anterior cruciate ligament deficiency had a quadriceps avoidance gait pattern. The quadriceps avoidance gait pattern was present in all but one of the eight patients in the chronic group, whereas only half in the early and intermediate groups had this adaptation.

A significant linear relationship existed between the early midstance knee moment and its corresponding angle of knee flexion ($p < .001$) (Fig 2). The rate of change (slope of regression line) between the knee moment and corresponding knee flexion angle were not significantly different between the two groups ($p = 0.186$), although the intercepts of the regression lines for the two groups were significantly different ($p < .0001$). The predicted knee flexion angle for the patients with anterior cruciate deficiency was significantly greater than that of the control group for the mean early midstance moment of the control group (2.1% body weight times height; $p < .003$) and the mean early midstance moment of patients with anterior cruciate deficiency (0% body weight times height; $p < .0001$).

The maximum flexion moment during stance in the anterior cruciate ligament deficient group (1.0% ± 0.9% body weight times height) was reduced significantly when compared with the control group (2.3% ± 1.2% body weight times height) (Table 2) ($p < .001$). The maximum flexion moment also had a tendency to decrease even further as time after injury increased. The chronic group had a maximum knee flexion moment of only 0.5 ± 0.4% body weight times height as compared with the early group of 1.2% ± 1.1% body weight times height ($p = 0.3$).

During terminal stance, the patients in the chronic group had a significantly increased
Relationship Between Knee Angle and Early Midstance Knee Moment

![Graph showing relationship between knee angle and early midstance knee moment](image)

**Fig 2.** The early midstance knee flexion moment and the corresponding knee flexion angle were significantly correlated. Moreover, the intercepts of the best fit line for the anterior cruciate deficient group and control group were significantly different although there was no statistically significant difference between the slopes of the two groups. Thus, for a given moment the predicted knee flexion angle of the subjects with an anterior cruciate deficiency was greater than that of the control subjects.

Knee extension moment compared with the subjects in the control group (p < 0.03)(Table 2). This increase in the terminal stance extension moment appeared to develop over time. The patients in the early and intermediate groups had a terminal stance extension moment not significantly different from that of the control group (−2.2 ± 1.1% body weight times height) (p = 0.68 early; p = 0.80 intermediate) while the moment of the chronic group was significantly greater than that of the control group (−3.9 ± 1.6% body weight times height). Likewise there was a trend for the patients in the chronic group to have an increased moment when compared with the patients in the early and intermediate groups (p = 0.09). The maximum knee extension moment for the entire stance phase also was increased terminal stance significantly when comparing the entire anterior cruciate ligament group with the control group (p < 0.03) (Table 2).

As time after the injury to the anterior cruciate ligament increased, there was a significant decrease in the terminal extension knee angle between the early and chronic groups (p < 0.01). Moreover, in the chronic group the terminal extension knee angle was significantly less than the normal subjects (p < 0.03) whereas that of the early and intermediate groups were not statistically different from normal (p = 0.1 early; p = 0.5 intermediate) (Fig 3). The terminal extension knee angle decreased from 8° ± 5° in the early group, to 5° ± 3° in the intermediate group, to 2° ± 3° in the chronic group (Table 3). For the control group, the terminal extension angle was 6° ± 4°. The remaining knee kinematics (minimum knee flexion, midstance knee flexion, and maximum knee flexion angles) were not significantly different between the anterior cruciate ligament deficient groups and the control group.

**Fig 3.** Sagittal plane knee angle during gait for the chronic anterior cruciate deficient group and control group. Minimum knee flexion angle, midstance knee flexion angle, terminal extension knee angle, and maximum knee flexion angle were evaluated.
**TABLE 3. Sagittal Plane Knee Angles During Gait**

<table>
<thead>
<tr>
<th>Subject Group</th>
<th>Number of Subjects</th>
<th>Minimum Knee Flexion Angle (°)</th>
<th>Midstance Knee Flexion Angle (°)</th>
<th>Terminal Extension Knee Angle (°)</th>
<th>Maximum Knee Flexion Angle (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal subjects</td>
<td>30</td>
<td>(-3 \pm 5)</td>
<td>(18 \pm 6)</td>
<td>(6 \pm 4)</td>
<td>(67 \pm 4)</td>
</tr>
<tr>
<td>All patients with anterior cruciate ligament deficiency</td>
<td>30</td>
<td>(2 \pm 3)</td>
<td>(17 \pm 5)</td>
<td>(6 \pm 5)</td>
<td>(66 \pm 5)</td>
</tr>
<tr>
<td>Time interval groups</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Early group</td>
<td>15</td>
<td>(1 \pm 3)</td>
<td>(18 \pm 5)</td>
<td>(8 \pm 5)</td>
<td>(67 \pm 4)</td>
</tr>
<tr>
<td>Intermediate group</td>
<td>9</td>
<td>(4 \pm 3)</td>
<td>(16 \pm 4)</td>
<td>(5 \pm 3)</td>
<td>(65 \pm 7)</td>
</tr>
<tr>
<td>Chronic group</td>
<td>6</td>
<td>(2 \pm 2)</td>
<td>(15 \pm 5)</td>
<td>(2 \pm 3)**,†</td>
<td>(65 \pm 4)</td>
</tr>
</tbody>
</table>

*Values are mean ± standard deviation.

**Significant difference \((p < 0.05)\) when compared with control group.

†Significant difference \((p < 0.05)\) when compared with early group.

**DISCUSSION**

The results of this study suggest that patients with anterior cruciate ligament deficiency adapt to their injury over time. Each of the peak external moments calculated for the knee during stance phase (midstance knee moment, terminal stance moment, and the maximum flexion and extension moments) showed either a reduction in the magnitude of the external flexion moment or an increase in the magnitude of the external extension moment. These changes in the moments were interpreted to represent a net reduction or avoidance in quadriceps use and an accentuation of hamstring use. Thus, a new phasing between the knee flexors and extensors in which the use of the quadriceps is reduced and the use of the knee flexors is increased is established over time.

The lack of an external flexion moment during early midstance (quadriceps avoidance gait) would be more consistent with a reduction in quadriceps activity than an increase in hamstring activity. From an anatomic viewpoint the hamstrings do not serve as effective synergists to the anterior cruciate ligament when the knee is near full extension. The patients' ability to compensate for the loss of the anterior cruciate liga-
tients with anterior cruciate ligament deficiency. As time after injury to the anterior cruciate ligament increased, there was a tendency for decreased knee flexion moments. A patient’s initial response to injury may be to walk with his or her knee flexed slightly more when one is generating the early midstance knee flexion moment. As time after injury increases, however, patients adapt and tolerate a straighter knee because the magnitudes of the external flexion moments are less.

In vivo studies of strain in the anterior cruciate ligament have revealed that the quadriceps is responsible for inducing the greatest strain in the anterior cruciate ligament during level walking at the point of terminal extension of the knee. It is not surprising, therefore, that no differences between the patients with anterior cruciate ligament deficiency and the control subjects were found in maximum knee flexion angles during level walking. Patients with anterior cruciate ligament deficiency tend to function more normally in activities in which the knee is flexed more than 40°.

Understanding adaptations during gait and their relationship to the stability of the knee joint may help explain and, eventually, help predict the clinical outcomes of patients with anterior cruciate ligament deficiency. How the adaptation is established over time, the functional role of adaptation during gait and during possible strenuous athletic activities may explain some of the results borne out in clinical studies. Daniel et al described in their prospective outcome study on the fate of the patient with anterior cruciate ligament deficiency that 61% of the patients were able to cope with their injuries although many were symptomatic. The remaining patients underwent reconstruction at varying time intervals. Daniel et al found that the hours per year of participation in strenuous athletic activities was the most important predictor of the need for future meniscal ligament surgery.

The goal of conservative treatment in anterior cruciate ligament deficiency is to rehabilitate the muscles surrounding the knee so that they can dynamically compensate for the loss of anterior cruciate ligament function. Some authors have emphasized hamstring strengthening because the hamstring muscles are protagonists of the anterior cruciate ligament when the knee is flexed. The authors’ results and the dynamic electromyography studies of others have suggested the presence of increased and prolonged hamstring activity in patients with anterior cruciate ligament deficiency. The increased external extension moments found in this study suggest that the hamstrings work to stabilize the knee during certain periods of stance phase. These findings support the role of hamstring strengthening as an integral part of rehabilitation by adding functional stability to the knee of the patient with anterior cruciate ligament deficiency.

The decreased external flexion moments and increased external extension moments, therefore, may represent an adaptation that decreases the abnormal anterior translation of the tibia by reducing the anterior pull of the quadriceps and increasing the stabilizing effect of the hamstrings. These gait changes were significantly more pronounced in the chronic group of patients when compared with the earlier groups of patients. This supports the premise that gait adaptations in patients with anterior cruciate ligament deficiency develop gradually over time.

This study is a cross sectional representation of patients with anterior cruciate ligament deficiency. A limitation of this study is that patient observation was not carried out longitudinally through time. A prospective study that analyzes patients who have adapted successfully to their injury without surgery at specified time intervals would better assess the natural history of the anterior cruciate ligament deficient state. A prospective study also would determine better whether the small but statistically significant change in the terminal knee extension has clinical significance. The results of this study provide a basis for conducting the more time consuming and costly prospective study.
The gradual development of functional adaptations during time supports the hypothesis that there is a subconscious reprogramming of the locomotive process that protects the knee from excessive anterior translation of the tibia. The interval changes in gait show that the reprogramming process is adaptable. The interval changes also may develop as the secondary restraints (medial meniscus) to anterior translation of the proximal tibia begin to stretch out.

Gait analysis provides a means to detect these subtle changes in the function of the knee that may have a role in predicting the outcomes of therapeutic intervention. Better understanding of how these adaptations change with time and what effect these changes have on the menisci and other ligaments may help identify patients with anterior cruciate deficiencies who are at a greater risk of having an unstable knee or subsequent degenerative changes develop.

References


