Gait Adaptations by Patients Who Have a Deficient Anterior Cruciate Ligament*

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ABSTRACT: Sixteen patients who had unilateral deficiency of the anterior cruciate ligament and ten healthy control subjects were analyzed during level walking, jogging, and ascending and descending stairs. Kinematic and kinetic findings for the right and left hips, knees, and ankles of all of the patients and control subjects were recorded during each activity. Substantial differences from normal function were observed for both limbs of the patients during level walking and during jogging. The magnitude of the maximum moment that tended to flex the knee was reduced the most (140 per cent) during level walking. It was reduced less (30 per cent) during jogging, it was not changed while the patient descended stairs, and it was slightly increased while he or she ascended stairs.

The reduction in the magnitude of the flexion moment about the knee was interpreted as the patient’s effort to reduce or avoid contraction of the quadriceps. Reduction of the flexion moment reduces any contraction of the quadriceps because there must be a mechanical balance between the external moment (due to body weight and the weight and inertia of the segment of the limb) that tends to flex the knee and an internal moment (generated by contraction of the quadriceps) that tends to extend the knee. This so-called quadriceps-avoidance gait was related to the angle of flexion of the knee when the maximum flexion moment occurred during each activity. This angle of flexion was 20 degrees during walking, 40 degrees during jogging, and approximately 60 degrees during stair-climbing. We think that this correlation between the quadriceps-avoidance gait and the angle of flexion of the knee meant that the patients altered their gait to avoid the anterior displacement of the proximal end of the tibia that is normally produced when the quadriceps contracts while the knee is in nearly full extension. In this study, 75 per cent of the patients had a quadriceps-avoidance gait.

CLINICAL RELEVANCE: The findings in this study indicate that when the anterior cruciate ligament is deficient, even the low-stress activity of walking on a level surface may be performed in an abnormal manner. This abnormal function could have long-term implications related to the changes that sometimes develop in knees in which a ruptured anterior cruciate ligament was never repaired or reconstructed.

The changes in the function of the lower extremity that occur after injury to the anterior cruciate ligament are not well understood. This type of information is needed for optimum management of patients who have deficiency of the anterior cruciate ligament. Noyes et al.10,11 found that approximately one-third of patients who had an anterior cruciate-deficient knee compensated enough to pursue recreational activities, another third compensated but had to discontinue many activities, and one-third had poor function. Whether the management of an anterior cruciate-deficient knee should be operative or non-operative remains controversial.

Noyes et al. carried out a long-term follow-up study of young, active patients who had chronic anterior cruciate insufficiency that either had been previously undiagnosed or had been operated on unsuccessfully10. They reported a 44 per cent prevalence of both degenerative changes and moderate or severe symptoms during activities of daily living. On the basis of these observations, many surgeons have recommended operative repair and reconstruction to young patients who wish to remain active in sports that involve running and cutting (a side-step maneuver to make a 90-degree change in direction).

The variable natural history and the progression of degenerative disease in some patients but not in others who have similar injuries suggest that some patients who have cruciate deficiency make functional adaptations. To our knowledge, the nature of these adaptations during activities of daily living has not been evaluated.

Functional adaptations were demonstrated while patients who had anterior cruciate insufficiency performed a side-step cutting maneuver. The adaptation consisted of more-than-normal flexion of the hip and knee during the part of the cutting cycle when high loads are transmitted across the knee joint. When the knee is flexed more, the hamstrings are in a position to stabilize the tibia more efficiently and to prevent abnormal anterior translation and

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internal or external rotation of the tibia at the knee. This apparent compensatory maneuver increases moments that tend to flex both the hip and the knee and necessitates additional activity of the quadriceps to maintain stability. Thus, adaptations in function of the knee to compensate for anterior cruciate deficiency seem to be accomplished by muscular forces that stabilize the knee during strenuous activities.

It is also possible that changes in function occur during the less strenuous activities of daily living. When a knee is flexed between 0 and approximately 45 degrees, any contraction of the quadriceps tends to displace the proximal end of the tibia anteriorly, thereby producing strain in the anterior cruciate ligament. In the absence of function of the anterior cruciate ligament, a patient might, therefore, subconsciously avoid contracting the quadriceps to avoid displacing the tibia anteriorly during activities such as walking, jogging, or ascending and descending stairs. The extent of this effect depends on both the force of contraction of the quadriceps and the amount of flexion of the knee. At present, very little is known about the function of the knee during the activities of daily living in patients who have a deficient anterior cruciate ligament.

The goal of this study was a better understanding of the changes in function of the knee that occur while patients who have a deficient anterior cruciate ligament in one knee walk, jog, and ascend and descend stairs.

### Materials and Methods

Sixteen patients who had unilateral anterior-cruciate deficiency were selected for study on the basis of arthroscopic or operative data that had been obtained at the time of reconstruction of the anterior cruciate ligament. Before treatment of the complete rupture, gait studies had been performed. Of the sixteen patients, five had had an isolated tear of the anterior cruciate ligament and eleven had had, in addition, a minor meniscal lesion. Six of the eleven lesions were in the medial meniscus; two, in the lateral meniscus; and three, in both menisci. Not more than 25 percent of any torn meniscus had been removed. No other ligaments were injured, as determined by examination under anesthesia at the time of reconstruction.

The study population consisted of fourteen men and two women. The mean age was 26 ± 5 years; the mean height, 1.75 ± 0.15 meters; and the mean weight, 80 ± 10 kilograms. Each patient was examined clinically with the pivot-shift and Lachman tests, as well as with the posterior drawer test and medial and lateral laxity tests with the knee flexed 30 degrees (Table 1). These clinical tests were not used to select the patients for the study, but rather to provide additional documentation of the arthroscopic or operative findings at the time of reconstruction.

There was no significant difference between the mean circumferences of the thighs on the injured and uninjured sides (p > 0.05). The alignment of the knees, which was measured while the patient stood, averaged 4 degrees of valgus angulation, and there was no significant difference

### Table 1

<table>
<thead>
<tr>
<th>Test*</th>
<th>Mean</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lachman</td>
<td>1.6</td>
<td>1.0</td>
</tr>
<tr>
<td>Anterior drawer</td>
<td>1.4</td>
<td>0.6</td>
</tr>
<tr>
<td>Posterior drawer</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Pivot shift</td>
<td>2.5</td>
<td>1.9</td>
</tr>
<tr>
<td>Medial laxity at 30°</td>
<td>0.8</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lateral laxity at 30°</td>
<td>0.4</td>
<td>0.7</td>
</tr>
</tbody>
</table>

* The patients were selected on the basis of an operative finding of a complete rupture of the anterior cruciate ligament. The clinical findings were not used in the selection process. In the control subjects, the results of all of the tests were negative.

† The findings were graded 0 to 4+, with 0 being normal and 4+ indicating the most laxity.

between the normal and injured knees. No patient had pain in the knee or another musculoskeletal disorder.

A control group of five healthy men and five healthy women was selected on the basis of age, height, and weight. The mean age of these normal subjects was 26 ± 5 years; the mean height, 1.67 ± 0.20 meters; and the mean weight, 62 ± 12 kilograms. No operation had been done on any joint in the lower extremities of the control subjects, and no control subject had any deformity or neuromuscular disorder that might impair normal walking. All clinical tests for stability of the knee were normal.

In the gait laboratory, the patients and the control subjects were tested with identical protocols during walking, jogging, and ascending and descending stairs. The walking and jogging were done on a ten-meter walkway. Data were collected during the middle stride of several strides, with the measurements starting just before the foot reached the force-plate. After this stride, each subject could then take several strides of deceleration after the foot of the limb that was being tested had lifted off the force-plate.

The subjects ascended and descended the stairs of a staircase that has been described previously. The measurements were made while the subjects stepped onto the bottom step, which rested on the force-plate. Data were collected for the affected and normal lower limbs of the patients who had a deficient anterior cruciate ligament and for both lower limbs of the control subjects.

The instrumentation, which has been described previously, included a two-camera optoelectronic digitizer, light-emitting diodes, a multicomponent force-plate, and a minicomputer. Placement of light-emitting diodes on the test subjects, determination of the geometric centers of the joint, and recording of the kinetic data for the hip, knee, and ankle were done as previously described. About each joint, external moments were calculated with the ground-reaction force and the weight and inertia of the segment of the limb. The external moments about the three joints were converted into vector components aligned along the axes of

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flexion-extension, abduction-adduction, and internal-external rotation for each of the joints. All moments were normalized to body weight and height to allow comparisons between the two knees of each patient and between the patients and the control subjects.

The analysis focused on the moments that tend to flex and extend the knee joint, and the corresponding angle of flexion of the knee during stance phase. This analysis involved determination of the maximum moment that tended to flex or extend the knee joint during stance phase as well as the angle of flexion of the knee when the maximum moment was recorded. We are reporting the moments that acted on the joint (external moments) since they were measured directly. However, on the basis of mechanical equilibrium, it was inferred that opposing internal moments of equal magnitude must have been generated to balance the external moments that were measured. For example, when an external moment tends to flex the knee, an opposing internal moment (generated primarily by the quadriceps mechanism) is needed to maintain equilibrium. The internal moment that balances the flexion moment (the moment that is provided by the quadriceps) actually reflects the net effect of the internal moments that are generated by the quadriceps and hamstring muscles (the extension moment produced by the quadriceps minus the flexion moment produced by the hamstrings), since simultaneous contraction of these muscle groups is possible. In this report, the terms net quadriceps moment and net hamstring moment will be used to refer to internal imbalances toward either greater activity of the quadriceps or greater activity of the hamstrings, as determined by the external moment that is being balanced.

Differences between the average values for the groups were analyzed with the Student t test to determine the levels of significance.

**Results**

During all of the activities that were studied, 75 per cent of the patients who had anterior cruciate deficiency made the same type of functional adaptation during level walking, and the other 25 per cent had a normal gait. Level walking produced the largest change from normal in the external flexion moment about the knee. Smaller changes were found during jogging and during ascending and descending stairs. During all of the activities that were tested, the magnitude of the change in the external flexion moment was largest when the knee was near full extension and was subjected to a flexion moment.

**Level Walking**

During level walking, the changes in the moments that tended to flex or extend the knee joint were related to the angle of flexion of the knee at the time when the change occurred (Fig. 1). Normally, during stance phase, the magnitudes and directions of the sagittal-plane moments about the knee follow a biphasic pattern as the moment about the knee changes from one that tends to produce extension at foot-strike, to a flexion moment at mid-stance, to an extension moment in late mid-stance, and finally to a flexion moment near toe-off. For the cruciate-deficient knees, the extension moments at foot-strike (when the knee is normally near full extension) were significantly greater (p < 0.05) than the comparable moments for the knees of the control subjects (Table II).

Between foot-strike and mid-stance, a normal knee flexes an amount that ranges from 0 to approximately 20 degrees (Fig. 1). At mid-stance, there is normally an external flexion moment (equivalent to 2.9 per cent of body weight multiplied by height), which is balanced by a net internal extension moment that is produced by contraction of the quadriceps and that maintains equilibrium. The patients who had anterior cruciate deficiency did not have this large external-flexion moment (Table II). Instead, they had an external extension moment that was balanced by a net internal-flexion moment, produced by contraction of the hamstrings during mid-stance. The patients also tended to have a characteristic temporal pattern of flexion and extension moments. We called this pattern, in which no net quadriceps (extension) moment was necessary during mid-stance, the quadriceps-avoidance pattern. In the present study, 75 per cent of the patients adopted this quadriceps-avoidance pattern. The remaining 25 per cent had the normal biphasic pattern of moments.
In the patients who had a deficient anterior cruciate ligament, some of the adaptive changes in the flexion-extension moments about the knee were accompanied by changes in the moments about the hip. During gait, the normal pattern of the flexion and extension moments about the hip is sinusoidal (Fig. 2). In this pattern, the moment about the hip tends first to flex the hip, starting at footstrike, and then to reverse direction at mid-stance. Thereafter, a moment that tends to extend the hip persists from mid-stance to toe-off. The patients who had anterior cruciate deficiency tended to have a significantly greater maximum

(3 degrees) during level walking occurred at foot-strike. This is the only time during the normal gait cycle when there is an external force that could cause such anterior displacement. However, when the knees of the patients who had anterior cruciate deficiency approached full extension (3 to 5 degrees of flexion), and maximum anterior shearing would have been expected, the patients did not appear to adapt the gait to either reduce or avoid this force. The maximum anterior shearing force was equivalent to 8.3 per cent of body weight multiplied by

During level walking by patients who had anterior cruciate deficiency, an external extension moment about the knee persisted throughout most of stance phase. In the presence of this moment, there is no need for activity of the quadriceps while the knee is near full extension. Normally, the necessary extension moment is produced by the quadriceps and is resisted by the anterior cruciate ligament. The asterisks identify the times during stance phase when the moments about knees of the control subjects and the patients were significantly different. See the text for definitions of net quadriceps and net hamstring moments.

flexion moment about the hip than did the control subjects (p < 0.05) (Table II). This increase in the flexion moment about the hip occurred during the early part of stance phase and was consistent with the larger-than-normal moment that tended to extend the knee at foot-strike (Fig. 2). However, the amounts of flexion and extension of the hip did not differ significantly between the patients and the control subjects (p > 0.05).

During all activities of the patients, the external shearing force that tended to displace the tibia posteriorly exceeded the external anterior shearing force on the tibia height in the normal group and 12.9 per cent of body weight multiplied by height in the patients (Table III).

The patients tended to walk with a symmetrical gait, so that the abnormality on the affected side was reproduced on the contralateral side (Tables II and III). Thus, the changes in the flexion moment about the knee and the adaptive changes in the moments about the hip were evident in both the affected limb and the unaffected limb during walking. At the ankle, however, there were no differences between the patients and the control subjects in any of the parameters that were studied.

FIG. 1

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TABLE III
EXTERNAL MOMENTS AND POSITIONS OF THE HIP AND KNEE AND SHEARING FORCES ON THE TIBIA DURING THE STANCE-PHASE OF THE STUDIED ACTIVITIES*

<table>
<thead>
<tr>
<th></th>
<th>Walking</th>
<th>Jogging</th>
<th>Ascending Stairs</th>
<th>Descending Stairs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Control</td>
<td>Deficit</td>
<td>Intact</td>
<td>Control</td>
</tr>
<tr>
<td>No. of patients</td>
<td>10</td>
<td>16</td>
<td>16</td>
<td>10</td>
</tr>
<tr>
<td>Max. hip flexion moment†</td>
<td>±3.1</td>
<td>±4.9</td>
<td>±5.7</td>
<td>±4.4</td>
</tr>
<tr>
<td>Max. angle of hip flexion (degrees)</td>
<td>24.6</td>
<td>18.2†</td>
<td>20.8</td>
<td>23.2</td>
</tr>
<tr>
<td>Angle of knee flexion at mid-stance (degrees)</td>
<td>23.9</td>
<td>19.6†</td>
<td>20.5</td>
<td>44.3</td>
</tr>
<tr>
<td>Max. knee flexion moment‡</td>
<td>±2.5</td>
<td>±3.4</td>
<td>±4.5</td>
<td>±5.3</td>
</tr>
<tr>
<td>Ant. shearing force on tibia‡</td>
<td>8.3</td>
<td>12.9</td>
<td>13.9</td>
<td>11.0</td>
</tr>
<tr>
<td>Post. shearing force on tibia‡</td>
<td>29.0</td>
<td>22.3</td>
<td>21.7</td>
<td>117</td>
</tr>
</tbody>
</table>

* Mean and standard deviation.
† Difference significant (p < 0.05) when compared with the control subjects.
‡ Per cent body weight multiplied by height.
§ Minus sign indicates a change from a flexion to an extension moment.

Jogging

When the patients began to jog, the greatest change in the knee-joint loads, compared with that during level walking, was the increase in the moment that tended to flex the knee (Table III). In the patients, this flexion moment, which normally persists throughout the support phase of gait and peaks at mid-support, was approximately 4.5 times greater during jogging than during level walking. Although the pattern of the flexion and extension moments was the same as that in the control subjects and in the patients during jogging and level walking, at mid-stance the peak flexion moment about the affected knees of the patients was significantly smaller (p < 0.05) than that in the control subjects (9.0 ± 3.8 compared with 13.1 ± 5.3 per cent of body weight multiplied by height). Therefore, the patients made an adaptation that reduced the net extension (quadriiceps) moment during this activity. Despite these differences, there was no difference between the speeds at which the patients and the control subjects jogged (average for both groups, 2.8 ± 0.5 meters per second). Finally, during jogging, there was no significant difference between the two groups with respect to the amount of flexion of the knee at mid-stance; the average value was 44 degrees for both groups.

The adaptation in the cruciate-deficient limbs was also evident in the normal, contralateral limbs of the patients since the patterns of loading and of movement of the joints were symmetrical during jogging. As a result, the magnitudes of the moments about the knee and the amounts of flexion of the knee at mid-stance in the affected and unaf-
fected limbs of the patients did not differ significantly during jogging (p > 0.05).

**Descending Stairs**

Descending stairs was associated with a large moment (8 per cent body weight multiplied by height) that tended to flex the knee (Table III). Interestingly, the patients did not avoid or reduce this large flexion moment about the knee, even though this moment was substantially larger than the moment during level walking (2.8 per cent body weight multiplied by height). However, as the patients descended stairs, the average angle of flexion of the knee was 62.4 degrees when the maximum moment occurred. This was substantially more flexion than was associated with the maximum flexion moment of the knee during walking or jogging. This finding suggests that, in the absence of anterior cruciate-ligament function, the tendency to make functional adaptations is related not only to the magnitude and direction of the flexion moment, but also to the amount of flexion of the knee. The symmetrical function of the two limbs when the patients jogged was also evident as they descended stairs. However, there were no other differences between the patients and the control subjects when they descended stairs.

**Ascending Stairs**

As the patients and the control subjects ascended stairs, the maximum flexion moment about the knee occurred when the knee was flexed slightly more than 66 degrees. At this time, the mean maximum flexion moment about the knee was 6.7 per cent of body weight multiplied by height in the affected knees of the patients and 4.3 per cent of body weight multiplied by height in the knees of the control subjects (Table III).

Ascending stairs was the only activity during which the flexion moment was definitely greater about the cruciate-deficient knees than in the normal knees of the control subjects. Also, during the stance phase of ascending stairs, the maximum flexion angle about the knee and the maximum flexion moment of the knee occurred simultaneously, just as during level walking (Fig. 1). In addition to these changes in the amount of flexion of the knee, there was increased flexion of both hips of the patients compared with the control subjects when they were ascending stairs.

**Discussion**

The findings in this study indicate that patients who have a cruciate-deficient knee modify the way that they carry out ambulatory activities. Despite the relatively low loads on the knee that occurred during level walking compared with those during the other activities that were studied, the patients modified the patterns most during level walking. These modifications included a reduction or avoidance of the peak flexion moment about the knee when the knee was flexed 40 degrees or less.

This reduction or avoidance of the peak flexion moment during walking and jogging was interpreted as a modification that was adopted to reduce or avoid contraction of the quadriceps (a quadriceps-avoidance gait), because biomechanically there must be a balance between the external moment that tends to flex the knee (which was measured in the laboratory) and the net internal moment that is generated by contraction of the quadriceps. In this report, the term net internal moment was used because of the possibility of simultaneous contractions of the quadriceps and hamstrings. If such concurrent contractions were present, the net internal moment that was generated would be the difference between the internal moment that was produced by the quadriceps force and that produced by the opposing hamstring force. Therefore, if such concurrent contractions did occur, a net internal quadriceps moment would imply that the internal moment that was generated by the force in the quadriceps was greater than the moment that was generated by the hamstrings.

The tendency of the patients to avoid contraction of the quadriceps as the cruciate-deficient knee flexed while it was near full extension is consistent with the findings of other biomechanical studies of the relationship between contraction of the quadriceps and strain in the anterior cruciate ligament. In these studies, it was found that the strain in the anterior cruciate ligament due to contraction of the quadriceps reached a maximum when the knee was flexed between 15 and 25 degrees. In the present study, the patients substantially reduced or avoided any flexion moment of the knee when the knee was flexed less than 40 degrees. Thus, a smaller net moment was resisted by the quadriceps, and the anterior displacement of the tibia that is associated with absence of the anterior cruciate ligament was avoided.

It was also shown that, when the knee was flexed beyond 60 degrees, contraction of the quadriceps decreased strain in the anterior cruciate ligament, a finding that was consistent with those in our study. Our patients tended to function more normally during activities in which the quadriceps contracted while the knee was flexed beyond 60 degrees. Thus, we found that the maximum flexion moment of the knee was normal when the knee was flexed 60 degrees as the patients descended stairs (Table III). Similarly, when the patients ascended stairs, the peak flexion moment of the knee occurred at mid-stance, when the knee was flexed approximately 66 degrees.

In contrast to the changes in gait that were related to the magnitude of the moments about the knee, there was no evidence of any attempt to minimize the external forces that tend to thrust the tibia forward at foot-strike. During level walking, an anterior shearing force developed only when the knee was near full extension (Table III). Typically, this shearing force was relatively low (approximately 10 per cent of body weight multiplied by height). Possibly, stability of the knee with respect to shearing forces was provided by the secondary restraints that prevent anterior displacement of the tibia when the knee is at or near full extension. In these positions, no adaptive muscular activity is needed.

This study was a first step toward the identification of the mechanisms that are involved in the functional adap-
ations of the gait of patients who have anterior cruciate deficiency. Presumably, these adaptations are the patient’s subconscious effort to avoid the excessive anterior displacement of the proximal part of the tibia that can occur in the absence of function of the anterior cruciate ligament\(^1\). It is not likely that the adaptations were the result of stimuli that recurred during each walking cycle. It is more probable that they represented early adaptations to the loss of function of the anterior cruciate ligament after injury and the subsequent reprogramming of the locomotor process so that excessive anterior displacement of the tibia was prevented. The rhythmic and symmetrical nature of the adaptations in both the cruciate-deficient limb and the contralateral limb supports this hypothesis. Furthermore, it is not likely that the necessary instantaneous adaptations in the ways that muscles contract could occur in response to stimuli during each stride cycle. Were this the case, the adaptations would have occurred after the tibia had been displaced and, therefore, would have resulted in less rhythmic patterns and a greater tendency for the gait to be asymmetrical. Whatever the mechanism or mechanisms of these changes, they indicate that the healthy limb cannot be used as a control in the evaluation of function of an injured limb\(^1\).

The effect of muscle contraction on the mechanics of the knee joint has been demonstrated experimentally\(^1\). The importance of maintaining muscle mass after an injury or operation about the knee has long been recognized by orthopaedic surgeons. After rupture of the anterior cruciate ligament, rehabilitation of the quadriceps and strengthening of the hamstrings to stabilize the tibia\(^6,12-16\) has been emphasized. Patients who maintain or increase the strength of the muscles of the thigh after rupture of the anterior cruciate ligament have better function of the knee\(^6\). It does not seem likely that patients who have a rupture of the anterior cruciate ligament avoid flexion moments of the knee while walking and jogging because the quadriceps is weak. In this study, the flexion moments that were associated with the more demanding activity of ascending stairs were greater about the cruciate-deficient knees than about the normal knees (Table III).

Gait analysis can be useful for evaluating patients who have an injury to the knee because it detects subtle changes in the function of the limb. Even in patients who have asymptomatic anterior-cruciate deficiency, the mechanics of the knee joint are greatly altered by adaptive changes in patterns of gait. Although large moments and forces were recorded while the patients were jogging and climbing stairs, the percentage change in the function of the knee joint was greatest during level walking. These functional changes in walking can be expected to modify the over-all pattern of loading on anterior cruciate-deficient knees and, therefore, to cause abnormal loading on specific structures of these knees. Such changes may influence the long-term changes that are found in cruciate-deficient knees.

References