Gait biomechanics are not normal after anterior cruciate ligament reconstruction and accelerated rehabilitation

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ABSTRACT
DEVITA, P., T. HORTOBAGYI, and J. BARRIER. Gait biomechanics are not normal after anterior cruciate ligament reconstruction and accelerated rehabilitation. Med. Sci. Sports Exerc., Vol. 30, No. 10, pp. 1481-1488, 1998. Purpose: Accelerated rehabilitation for anterior cruciate ligament (ACL) injury and reconstruction surgery is designed to return injured people to athletic activities in approximately 6 months. The small amount of empirical data on this population suggests, however, that the torque at the knee joint may not return until 22 months after surgery during walking and even longer during running. Although the rehabilitation has ended and individuals have returned to preinjury activities, gait mechanics appear to be abnormal at the end of accelerated programs. The purpose of this study was to compare lower extremity joint kinetics, kinematics, and energetics between individuals having undergone ACL reconstruction and accelerated rehabilitation and healthy individuals. Methods: Eight ACL-injured and 22 healthy subjects were tested. Injured subjects were tested 3 wk and 6 months (the end of rehabilitation) after surgery. Ground reaction force and kinematic data were combined with inverse dynamics to predict sagittal plane joint torques and powers from which angular impulse and work were derived. Results: The difference in all kinematic variables between the two tests for the ACL group averaged 38% (all P < 0.05). The kinematics were not different between the ACL group after rehabilitation and healthy subjects. Angular impulses and work averaged 100% difference for all joints (all P < 0.05) between tests for the ACL group. After rehabilitation, the differences between injured and healthy groups in angular impulse and work at both the hip and knee remained large and averaged 52% (all P < 0.05). Conclusions: Results indicated that after reconstruction surgery and accelerated rehabilitation for ACL injury, humans walk with normal kinematic patterns but continue to use altered joint torque and power patterns. Key Words: ACL INJURY, KNEE, WALKING, RECONSTRUCTION SURGERY, BIOMECHANICS

Injury to the anterior cruciate ligament (ACL) produces distinct changes in lower extremity kinetics and energetics during gait. Whereas healthy individuals walk with an extensor torque at the knee between 10 and 45% of the stance phase (13,14,41), individuals with recent ACL deficiency walk with an extensor torque lasting nearly the entire stance phase (13). Over the next several years the extensor torque at the knee becomes reduced in ACL-deficient individuals and in many cases becomes a flexor torque (1,4,5,28). Along with this adaptation, the extensor torque at the hip in early stance eventually increases to approximately 1.5 times the value seen in healthy individuals (4,28).

Gait adaptations in individuals with ACL injury who have reconstruction surgery are less clear for two reasons. First, no comprehensive gait analyses have been conducted on this population and, second, the large variation in surgical and rehabilitation procedures and patient characteristics and their compliance with rehabilitation limit the generalizability of these potential results. One principle factor in the recovery from ACL injury and surgery is the rehabilitation protocol. During the past 10 yr there has been a shift from the standard, conservative rehabilitation program (7,39) to a more aggressive, accelerated protocol (9,20,26,30,31). Accelerated programs are designed to return the patient to full activity at 4-6 months after surgery, approximately twice as fast as the conservative approach. Accelerated programs generally emphasize full knee extension and immediate weight bearing on the first postoperative day, closed kinetic chain exercises by the third week, and easy running about the fifth week after surgery. Patients return to full athletic participation at about 6 months when the strength and range of motion (ROM) in the involved limb are similar to these measures in the contralateral limb.

Despite the acceptable strength and ROM measures at the end of the rehabilitation, there is evidence that the knee joint does not function normally during the complex actions of
strings and quadriceps strengthening with closed kinetic
analysis of these variables might provide information that can be
used to improve rehabilitation programs and the subsequent
biomechanics takes much longer than 6 months if they
return at all. The question arises as to the nature of the
biomechanical characteristics used by patients during gait at
the completion of an accelerated rehabilitation program. The
purpose of this study was to compare gait biomechanics
between individuals having undergone ACL reconstruction
and accelerated rehabilitation and healthy individuals. It was
hypothesized that although the rehabilitation program was
completed, the gait biomechanics would be different be-
tween the two groups. It was reasoned that a detailed anal-
ysis of these variables might provide information that can be
used to improve rehabilitation programs and the subsequent
long-term prognosis for people with surgically recon-
structed ACLs.

METHODS

Subjects. Eight ACL-injured subjects (mean age, 20.3
yr; mean mass, 74.2 kg), three females and five males,
volunteered for the study. All subjects had complete rupture
of the ACL and had never had a previous knee injury. Five
subjects were collegiate athletes, one participated in high
school athletics, and two were recreational athletes. There
was no other ligamentous injury in any subject although
there was some cartilage damage in each case. All subjects
had arthroscopically assisted, endoscopic, bone-patellar ten-
don-bone reconstruction using the central one-third of the
patellar tendon. All subjects completed an accelerated reha-
bilitation program similar to that described by Shelbourne
and Nitz (31). Emphasis was given to achieving early knee
extension and weight bearing. Active muscle contraction
was used to increase the range of knee joint motion. Ham-
strings and quadriceps strengthening with closed kinetic
chain exercises were started during the second to third week
using an exercise bicycle and stair stepper. The subjects
started jogging between the fourth and fifth weeks. The
entire rehabilitation program lasted 6 months. Twenty-two
healthy subjects, 14 males and 8 females, also volunteered
for the control group (mean age, 21.7 yr; mean mass, 73.7
kg). Control subjects had no history of lower limb pathol-
ogy. All subjects gave written informed consent according
to University and American College of Sports Medicine
policy.

Instruments. A force platform (AMTI, Watertown,
MA, Model LG6-4-2000) located in the center of a 20-m
level walkway was used to measure vertical and horizontal
ground reaction forces and the mediolateral moment at 1000
Hz. Sagittal plane kinematics were obtained with a video
camera (SONY Corp., Park Ridge, NJ, Model SSC M350)
and video cassette recorder (JVC, Elmwood Park, NJ,
Model HRSS100U) sampling at 60 Hz.

Protocol. The testing protocol was essentially identical
between the injured and control groups except that the
injured group was tested twice. The injured subjects were
tested 3 wk after surgery (within a few days of free walking
without assistance) and 6 months after surgery (the end of
the rehabilitation program). The control subjects were tested
on one occasion.

Circumference measures of the upper thigh, knee, ankle,
and metatarsal heads were obtained for the ACL-injured
limb or the right limb in the control subjects, along with
body weight. Reflective markers were then placed on the
lateral side of the shoe at the head of the fifth metatarsal
and heel, and on surface locations over the lateral malleolus,
lateral femoral condyle, greater trochanter, and shoulder on
each tested side. Subjects practiced walking along the walk-
way until they were comfortable and relaxed. A starting
point was then identified so that the subject would contact
the force platform in a normal stride with the appropriate
limb. Eight trials of data were collected for each subject at
each test. Trials were recollected if the subject altered his or
her stride to contact the force platform.

Data reduction. Video records were digitized with the
Peak Performance (Englewood, CO) system. Reflective
markers on the subject and one on the force platform were
digitized throughout the swing phase before contacting
the platform and stance phase on the platform (11). Markers
in four additional frames before and after these phases were
also digitized to improve the accuracy of the data near the
ends of the cycle.

High frequency error was removed from the digitized
position coordinates with a second-order Butterworth digital
filter. Cut-off frequencies were determined with the method
proposed by Winter (40) and they averaged approximately 7
Hz. The resultant position data were then interpolated to 200
Hz. Angular position was calculated for the hip, knee, and
ankle joints with zero degrees being the anatomical position
and positive values representing hyperextended hip and
knee joints and plantarflexed ankle joint. Joint angular ve-
locity was calculated with finite differences from the angular
position.

The lower extremity was modeled as a rigid, linked seg-
ment system. Magnitude of the segmental masses and loca-
tion of the mass centers along with their moments of inertia
were estimated from the position data using a mathematical
model (18), segmental masses reported by Dempster (10), and the individual subject's anthropometric data. Center of pressure was calculated from the ground reaction forces and the mediolateral moment on the platform. Center of pressure was expressed in the kinematic reference frame based on the digitized location of the force platform. Inverse dynamics using linear and angular Newtonian equations of motion were used to calculate the joint reaction forces and torques at each joint throughout the gait cycle. A support torque was calculated as the sum of the three joint torques (41). The support torque quantifies the total torque output from the extremity and provides a quantitative assessment of the support and propulsive effort of the musculature in the entire limb. It also provides a total torque value against which each of the individual joint torques can be compared to assess the relative contribution of the individual joints to the performance. All joint torques were expressed as positive values for extensor or plantarflexor torques. Joint powers were calculated as the product of the joint torques and angular velocities. Positive power indicated that the observed joint torques and angular velocities were in the same direction and the torque performed work to increase the energy of the skeletal system. Negative power indicated that the observed joint torques and angular velocities were in the opposite direction and the torque performed work to decrease the energy of the skeletal system.

**Data analysis.** ROM during the swing phase and average position during the stance phase were derived from each position curve. Extensor (or plantarflexor) angular impulses during the entire stance phase (support and ankle) or during the initial half of stance (hip and knee) were derived from the torque curves. Angular impulse is the area under a torque curve and extensor or plantarflexor angular impulses represent the areas under the positive phases of the torque curves in this study. Angular impulse quantifies the total contribution of a joint torque toward producing movement and it provides a better comparison than peak torque values. Gait changes can be adaptations in either the length of time a particular muscle group produces torque (14) or in the magnitude of torque produced by the muscle group (1). Angular impulse will account for either of these adaptations whereas peak values will not.

Positive work during the first half of stance (40 to ~70% of gait cycle) was calculated from the hip power curves and negative and positive work during this time (~45 to ~55% and ~55 to ~65% of gait cycle) were calculated from the knee power curves. Negative and positive work throughout stance (40 to ~83% and ~83% to 100% of gait cycle) were derived from the ankle power curves. These work phases correspond to phases H1, K1, K2, A1, and A2 for the hip, knee, and ankle joints from Winter (41). Positive and negative work at each joint were calculated as the area under the respective positive and negative portions of the power curves. Positive work indicated that the torque was produced through concentric muscle contraction that generated mechanical energy and contributed to propelling the individual. Negative work indicated that the torque was produced through eccentric muscle contraction that absorbed mechanical energy and contributed to decelerating the individual.

These variables were entered into a two-way, mixed factor, ANOVA (23) with knee condition (injured vs healthy) and time (first vs second test; control group had first test only) as the factors. Two direct comparisons were conducted: 1) first versus second test in the ACL-injured group and 2) ACL-injured, second test versus healthy controls, first test. All statistical decisions were based on an alpha level of 0.05.

**RESULTS**

The angular kinematics were different between the two tests for the injured group (Fig. 1, Table 1). ROM during swing was 10% smaller at the hip, 39% larger at the knee, and 32% larger at the ankle (all \( P < 0.05 \)) 6 months after surgery compared with 3 wk after surgery. Stance phase kinematics were also improved over the rehabilitation period and all lower extremity joints were flexed (or dorsiflexed) less during stance at 6 months compared with 3 wk after surgery. The average position of the hip, knee, and ankle joints were 48, 35, and 63% less flexed (all \( P < 0.05 \)) during stance 6 months after surgery compared with 3 wk after surgery. The angular kinematics showed excellent recovery at 6 months after surgery and were nearly identical to those of the healthy controls. None of the kinematic variables were statistically different between the injured group at 6 months after surgery and the control group (all \( P > 0.05 \)).

The joint torques during stance were also much different between the two tests for the injured group (Figs. 2 and 3).
The extensor angular impulse at the hip and plantarflexor angular impulse at the ankle were 38% and 35% smaller (both P < 0.05) at 6 months after surgery compared with 3 wk after surgery. In contrast, the extensor angular impulse at the knee during the first half of stance was 20% larger (P < 0.05) after 6 months of rehabilitation compared with 3 wk after surgery. The combined torque output at all three joints was summarized in the support torque. The support torque and angular impulse were unusually large soon after surgery but decreased 49% (P < 0.05) at 6 months after surgery.

The ACL-injured subjects showed a partial recovery in their stance phase joint torques after rehabilitation, but the torques remained different than the torques in the control group. Although the extensor angular impulse at the hip was reduced from the 3-wk level, it remained 37% larger (P < 0.05) than the control group value. The extensor angular impulse at the knee during the initial half of stance also showed only a partial recovery at 6 months after surgery. The impulse was only 57% (P < 0.05) of the corresponding impulse in healthy controls. The improvement in ankle joint kinetics was statistically complete at 6 months after surgery, and the difference between the plantarflexor impulse at this time and the value for the control group (17%) was not significant. Although two individual joints had different torques in the injured group at 6 months compared with those in the healthy controls, the combined changes in the individual joint torques produced a support torque that was statistically identical to the support torque in the controls. The difference in angular impulse from the support torque between groups was only 9% and not statistically significant.

The joint power and work characteristics were distinctly different between 3 wk and 6 months after surgery in the ACL-injured subjects (Figs. 4 and 5). The positive work at the hip in the first half of stance decreased 44% (P < 0.05) after 6 months of rehabilitation compared with the 3-wk value. The amount of negative and positive work done at the knee joint during the first half of stance changed during the initial 6 months following surgery. The negative work increased 250% and the positive work increased 267% (both P < 0.05) during this time. There was a 43% decrease (P < 0.05) in the amount of negative work done at the ankle joint during stance between the 3-wk and the 6-month tests. The increase in positive work done at the ankle (8%) in the ACL group was not significant.

As in the joint torques, the joint powers showed only a partial recovery after accelerated rehabilitation. The reduction of work done at the hip at 6 months compared with that at 3 wk after surgery still did not reduce the hip work to the level seen in control subjects. The work at the hip was 77% larger (P < 0.05) in the ACL-injured subjects at 6 months after surgery compared with the healthy subjects. The negative work done at the knee did not recover after 6 months to the level observed in the healthy subjects. This negative work was only 53% (P < 0.05) of the negative work done by the control group. The positive work done at the knee at 6 months also did not reach the level observed in the controls. The positive work in the injured subjects at 6 months was only 44% (P < 0.05) of the work observed in

### Table 1: Mean values and SDs across groups for kinematic variables.

<table>
<thead>
<tr>
<th>Variable</th>
<th>ACL-3 wk</th>
<th>ACL-6 months</th>
<th>Healthy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hip ROM swing</td>
<td>29.1 (4.8)</td>
<td>α</td>
<td>26.2 (1.9)</td>
</tr>
<tr>
<td>Hip pos. stance</td>
<td>-14.3 (3.2)</td>
<td>α</td>
<td>-7.4 (5.6)</td>
</tr>
<tr>
<td>Knee ROM swing</td>
<td>44.6 (5.1)</td>
<td>α</td>
<td>62.0 (4.4)</td>
</tr>
<tr>
<td>Knee pos. stance</td>
<td>-24.6 (4.8)</td>
<td>α</td>
<td>-16.1 (5.4)</td>
</tr>
<tr>
<td>Ankle ROM swing</td>
<td>20.9 (10.6)</td>
<td>α</td>
<td>27.5 (4.1)</td>
</tr>
<tr>
<td>Ankle pos. stance</td>
<td>-9.8 (6.7)</td>
<td>α</td>
<td>-3.8 (5.9)</td>
</tr>
</tbody>
</table>

All values in degrees; α: ACL 3 wk vs. 6 months, P < 0.05.

![Figure 2—Joint torque curves from the three groups. Positive values indicate extensor or plantarflexor torque. At 3 wk after surgery, there were large extensor (plantarflexor) torques at the hip and ankle and a low extensor torque at the knee during stance. The total support torque, the sum of the joint torques, was highly extensor and was necessary to support the injured subjects who were more flexed than healthy individuals. The joint torques improved after rehabilitation but only the ankle torque return to a normal value. The extensor torques at the hip and knee were still larger than and smaller than normal at the 6-month test.](http://www.wilkins.com/MSSE)
healthy subjects. The negative work done at the ankle joint did recover after 6 months to the level observed in the healthy subjects. The difference between the 6-month observation and the control value at the ankle (2%) was statistically nonsignificant ($P > 0.05$).

**DISCUSSION**

Numerous studies have evaluated ACL-injured individuals at various times after reconstruction surgery and rehabilitation. The majority of these investigations tested isokinetically for muscle strength measures (29,33–35,39) and arthrometers (e.g., KT-1000) for joint stability measures (19,25,30,31). These studies provided essential functional assessments of the knee itself and of the surgical and rehabilitation procedures applied to the knee. Few, if any, studies, however, have provided comprehensive evaluations of the biomechanics of the entire extremity during daily human movements even though injury to a single knee ligament causes neuromuscular adaptations throughout the lower extremity (4,12). In addition, although a reconstructed and rehabilitated knee may have acceptable muscle strength and stability, it is not clear that this knee would function normally during daily activities, particularly at the end of an accelerated rehabilitation protocol. The present work investigated biomechanical adaptations throughout the lower extremity during the daily activity of walking and provided a comprehensive, functional analysis of an injured limb after ACL reconstruction and rehabilitation.

The general movement pattern used in gait, as evaluated through the joint kinematics, was restored to normal after 6 months of accelerated rehabilitation. The initial response to reconstruction surgery was to walk with approximately $10^\circ$ more flexion at all joints, particularly during stance (Fig. 1). After rehabilitation, the joint position curves were nearly identical between the injured and control subjects and none of the comparisons was significant. The ACL-injured subjects returned to a more erect and normal style of walking after 6 months of rehabilitation compared with that at the start of the rehabilitation. Gait kinematics during stair climbing in ACL-reconstructed subjects also returned to normal after 6 months of accelerated rehabilitation from the same surgery as presently used (24).

Although the kinematics returned to normal after rehabilitation, the causative joint torques and powers made only a partial recovery. The joint torques improved at all three joints; however, only the torque at the ankle joint returned to normal (Figs. 2 and 3).
The torque at the knee was improved at 6 months, particularly in midstance, but it was still different than the knee torque in healthy subjects. Three weeks after surgery, ACL-reconstructed subjects used a continuous extensor torque throughout stance, unlike healthy individuals who switched to a flexor torque in midstance (Fig. 2, (13,14,41)). After rehabilitation, the ACL-injured subjects showed the proper phasic relationships and had alternating flexor, extensor, flexor, then extensor knee torques during stance, but they still had a decrement in the magnitude of the extensor torque and angular impulse in early stance compared with that in the healthy controls. Kowalk et al. (24) reported a similar reduction in knee torque for the same population while ascending stairs. As described by Kowalk et al., it is reasonable to observe reduced knee extensor torque at 6 months after surgery since the procedure harvested the central one-third of the patellar tendon. Other studies have also observed reduced knee extensor torque in isokinetic testing after reconstruction surgery (34,35,37). The reduced torque presently observed produced less negative and positive work during stance compared with that in healthy subjects. The reduction in negative work is in agreement with Juris et al. (22) who reported a decreased “force absorption” capability in the involved quadriceps during hopping and jumping at 6 months after ACL surgery and rehabilitation and with DeVita et al. (12) who showed reduced work in completely rehabilitated subjects during running.

The excessive extensor torque at the hip in stance shortly after surgery was reduced through rehabilitation but not to the level observed in healthy subjects. The atypical hip torque after rehabilitation was seen not as an increase in peak torque compared with healthy controls but as an extensor torque lasting longer into the stance phase. This longer lasting torque enabled the hip extensors to produce more angular impulse and work for the ACL-injured and rehabilitated subjects in the first half of stance compared with that in the healthy controls. In this study hip torque and power differed between the ACL-rehabilitated and healthy groups as a function of time and area under the curves but not in peak magnitudes. We chose to compare angular impulse and not peak torque because it is the torque applied over a period of time that changes joint angular velocity and ultimately produces skillful human movement. The assessment of peak values may not provide as much insight about the total effect or contribution of the muscles at a particular joint since they provide only a momentary assessment of the dynamic joint torque.

The increased output of the hip extensors in the rehabilitated subjects performed two important functions. The extensor torque provided a larger proportion of the total support torque during the initial half of stance compared with that in healthy subjects. The angular impulse generated by the hip extensors was 65% of the support angular impulse during the first half of stance in the rehabilitated, ACL-injured subjects compared with 40% in the healthy subjects. The hip extensors also produced most of the positive work used to generate forward velocity during the first half of stance. After rehabilitation, the ACL-injured subjects maintained forward progression with a much greater reliance on the hip extensors compared with healthy controls. In both
ACL-injured and healthy individuals, the hip and knee extensors produced a net positive amount of work while the ankle plantarflexors produced a net negative amount of work during the first half of stance (Fig. 4). After ACL reconstruction and rehabilitation, the hip extensors produced 83% of this work compared with only 56% in the healthy individuals. The increased output of the hip extensors during walking is in agreement with hip extensor function during stair ascent in ACL-reconstructed patients (24). These subjects used the hip extensors to produce a greater proportion of the total work done to lift themselves up the flight of stairs. Therefore, at 6 months after ACL reconstruction and accelerated rehabilitation, the hip extensors provide more vertical support and forward progression during the first half of stance compared with the contribution seen in healthy individuals. The results describing joint torques and powers at the hip and knee indicate that although the ACL-injured subjects completed an accelerated rehabilitation program and have returned to competitive athletics, they do not use normal kinetics and energetics during walking.

The support torque was nearly identical between the ACL-rehabilitated and healthy subjects. After 6 months of rehabilitation, the ACL-injured subjects were able to walk with less flexion at all joints compared with that at 3 wk after surgery. This more erect posture reduced the external flexor torques at each of the joints and enabled the subjects to walk with less total extensor effort.

The reduced knee torque and increased hip torque after rehabilitation compared with healthy subjects were probably a result of adaptations in force production by the quadriceps and hamstrings muscles. Many studies have shown that ACL-deficient subjects have reduced quadriceps and increased hamstrings EMG during gait (6, 15, 17, 32) and that these people use either a reduced or absent extensor torque at the knee and an increased extensor torque at the hip (1.4, 5, 13, 38). The present differences in the knee and hip torques between the ACL-reconstructed and rehabilitated and healthy subjects suggest that the injured subjects also had reduced quadriceps and increased hamstrings force during the stance phase of walking. It is well documented that maximal quadriceps force is reduced soon after ACL reconstruction surgery (34, 35, 39) and several years after surgery (2, 37). The present results suggest that subjects with ACL reconstruction and accelerated rehabilitation produce less quadriceps force during gait compared with that in healthy individuals even though only moderate levels of force are required.

The alterations in gait kinematics and kinetics during the rehabilitation period suggest the load on the repaired liga-

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