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Motion Alterations After Anterior Cruciate Ligament Reconstruction: Comparison of the Injured and Uninjured Lower Limbs During a Single-Legged Jump

Benoît Pairot de Fontenay, PT; Sebastien Argaud, PT; Yoann Blache, MS; Karine Monteil, PhD

Université de Lyon—Université Claude Bernard, France

Context: Asymmetries subsist after anterior cruciate ligament reconstruction (ACL-R), and it is unclear how lower limb motion is altered in the context of a dynamic movement.

Objective: To highlight the alterations observed in the injured limb (IL) during the performance of a dynamic movement after ACL-R.

Design: Cross-sectional study.

Setting: Research laboratory.

Patients or Other Participants: A total of 11 men (age = 23.3 ± 3.8 years, mass = 81.2 ± 17.0 kg) who underwent ACL-R took part in this study 7.3 ± 1.1 months (range = 6–9 months) after surgery.

Intervention(s): Kinematic and kinetic analyses of a single-legged squat jump were performed. The uninjured leg (UL) was used as the control variable.

Main Outcome Measure(s): Kinematic and kinetic variables.

Results: Jump height was 24% less for the IL than the UL ($F_{1,9} = 23.3$, $P = .001$), whereas the push-off phase duration was similar for both lower limbs ($P = .96$). Knee-joint extension ($F_{1,9} = 11.4$, $P = .009$), and ankle plantar flexion ($F_{1,9} = 22.6$, $P = .001$) were less at takeoff for the IL than the UL. The hip angle at takeoff was not different between lower limbs ($P = .09$). We found that total moment was 14% less ($F_{1,9} = 11.1$, $P = .01$) and total power was 35% less ($F_{1,9} = 24.2$, $P = .001$) for the IL than the UL. Maximal hip ($P = .09$) and knee ($P = .21$) power was not different between legs. The IL had 34% less maximal ankle power ($F_{1,9} = 11.3$, $P = .009$) and 31% less angular velocity of ankle plantar flexion ($F_{1,9} = 17.8$, $P = .004$) than the UL.

Conclusions: At 7.3 months after ACL-R, motion alterations were present in the IL, leading to a decrease in dynamic movement performance. Enhancing the tools for assessing articular and muscular variables during a multijoint movement would help to individualize rehabilitation protocols after ACL-R.

Key Words: knee, dynamic movement, hop test, rehabilitation

Key Points

- Kinematic and kinetic alterations were demonstrated in the injured leg at 7.3 months after anterior cruciate ligament reconstruction.
- These alterations led to decreased jump height during a single-legged squat jump in the injured leg.
- Enhancing tools for assessing articular and muscular variables during a multijoint movement would help to individualize rehabilitation protocols after anterior cruciate ligament reconstruction.

Anterior cruciate ligament (ACL) reconstruction involving bone-patellar tendon-bone (BPTB) or hamstrings tendon grafts has been commonly used after ACL rupture.[1] Ligament reconstruction often requires a long period of recovery, with a return to sport typically around 6.2 months after surgery.[2] However, the return to high-performance pivoting sports is not ensured. Sixty-seven percent were unable to return to their preinjury sport participation levels by 12 months after surgery.[3]

Postoperative follow up, therefore, is crucial to evaluate the functional states of patients and individualize rehabilitation programs to achieve optimal recovery. Currently, several variables can help to monitor postoperative follow up[4]: (1) clinical measures, such as edema, pain, mobility, and stability of the knee joint; (2) subjective measures, such as the subjective knee form of the International Knee Documentation Committee[5]; and (3) objective measures, such as the measurement of anterior translation of the tibia on radiographs and the assessment of muscular recovery. To evaluate muscular recovery, 2 main types of tests are performed: an isokinetic test[6] and functional tests.[6,7] The uninjured limb (UL) is used as a reference, and the goal of rehabilitation is to increase side-to-side symmetry.[6,8–10]

The isokinetic test helps to quantify muscular recovery by measuring peak muscle torque of the extensor and flexor muscles of the knee joint. Some authors[1,11] have shown deficits in the quadriceps and hamstrings muscles after ACL reconstruction. However, this test solely focuses on the knee joint and does not take into account the multijoint dimension of movements performed in sport activities.[12]

Functional tests use single-legged functional movements involving the hip, knee, and ankle joints to identify performance deficits between the lower extremities. During vertical jumps, jump height was 14% to 24% less in the injured leg (IL) than in the UL[13] 6 months after ACL reconstruction. Mohtadi et al[1] concluded that the results of functional tests did not differ with graft location. Functional tests use movements performed in sport activities, but they do not allow the identification of the deficit variables[7] in terms of specific limitations responsible for the decrease in performance. In addition, these tests do not allow deficits to be corrected during rehabilitation.

Some authors[14,15] have suggested the development of joint adaptations during multijoint movements after ACL reconstruction, consisting of modified joint positions and range of motion of the lower limb joints. Decker et al[14] reported greater hip-extension and ankle plantar-flexion angles at initial ground contact during landing in the injured group than in the control group, and Pfeifer and Banzer[15] observed that the range of motion of the knee joint during cycle single-legged jumps was less in the IL than in the UL. For kinetic analysis, Ernst et al[16] measured a lower maximal knee moment in the IL than the UL and equivalent maximal hip and ankle moments in both limbs. Castanharo et al[17] studied maximal power during a bilateral vertical jump and also noted a decrease in maximal knee power and equivalent maximal hip power in the ACL group compared with the control group. In these studies, joint and muscular variables were analyzed independently.

Therefore, the purpose of our study was to highlight the alterations observed in the IL during the performance of a dynamic movement after ACL reconstruction. Our aim was to bring additional information to the current knowledge in the field of movement analysis to help multidisciplinary teams improve rehabilitation after ACL reconstruction. We hypothesized that (1) jump height would be less in the IL than in the UL, (2) we would find kinematic alterations with a modification in the joint positions of the lower limb joints of the IL at takeoff, and (3) we would find kinetic alterations with decreases in maximal knee moment and power in the IL compensated for by an increase in hip and ankle maximal moments and powers.

METHODS

Participants

A total of 11 men (age = 23.3 ± 3.8 years, mass = 81.2 ± 17.0 kg) who underwent surgical reconstruction of unilateral isolated ACL tears with BPTB (n = 6) or hamstrings tendon (n = 5) grafts participated in the study. They took part in the experiment 7.3 ± 1.1 months (range = 6–8.5 months) after surgery, when they were identified as able to return to sport activities using the following criteria: no pain during activities of daily living or rehabilitation sessions, no episodes of "giving way," full range of motion at the knee joint, and in the last stage of the rehabilitation program. The rehabilitation protocols had a similar number of training sessions with similar content (ie, electrotherapy, neuromuscular reeducation, strengthening exercises, and functional training). Participants had no history of surgery or traumatic injury to the contralateral limb or of injury to the IL after the surgery. All participants provided written informed consent, and the study was approved by the Ethical Committee of the Université de Lyon – Université Claude Bernard.

Testing Procedures

The squat jump was chosen because this task is similar to movements performed in sport activities.[18] Upper limb motion was forbidden so that we could focus on lower limb motion. No countermovement was allowed, thereby eliminating the stretch-shortening cycle effect, which enabled us to analyze the capacity to generate force during the concentric muscular-contraction phase. Participants performed warm-up and jump-training sessions to become familiar with the task and minimize possible sources of bias, such as countermovement. Subsequently, each participant performed 6 maximal single-legged squat jumps: 3 jumps on the IL and 3 jumps on the UL in randomized order. The initial position was the preferred position they chose, and they were instructed to jump as high as possible without downward movement. They were told to keep their hands on their hips for the duration of the jump to avoid back movements.

Instrumentation

Reflective markers were placed on the following anatomic landmarks according to the anthropometric data of Winter[19]: fifth metatarsophalangeal joint, lateral malleolus, lateral femoral condyle, greater trochanter, and acromion process. Participants jumped with the foot on a force platform (Advanced Mechanical Technology, Inc, Watertown, MA) with a frequency of 1000 Hz while they were filmed in the sagittal plane with a 100-Hz camcorder (model UI-2220SE; Imaging Development Systems, Obersulm, Germany).

Data Analysis

Both kinematic and kinetic data of the push-off phase of a single-legged squat jump were analyzed. The goal was to assess the recovery in terms of performance after ACL reconstruction. Kinetic and kinematic data were smoothed with a zero-lag, fourth order, low-pass Butterworth filter with cutoff frequencies of 15 Hz and 10 Hz, respectively. Kinetic data were down-sampled to 100 Hz. A 4 rigid-segments model (foot, shank, thigh, and upper body [ie, head, arms, and trunk]) was obtained from the digitalization of the center of the landmarks. The mean and standard deviation (SD) of the vertical ground reaction force (Rz) was determined over the first second in which the participant held the initial position. After this first second when Rz decreased more than 3 SDs below body weight, the trial was discontinued. The beginning of the push-off phase (POP) corresponded to the instant when, after the first second, Rz increased more than 2 SDs above body weight (adapted from Vanrenterghem et al[20]). Next, the kinematic and kinetic data were synchronized. For this purpose, we determined the end of the POP for the kinematics and kinetics, which corresponded to the last frame when the foot was in contact with the ground and the last time sample before Rz decreased to zero, respectively. For further analysis, the best of the 3 trials, based on the maximal height reached during flight, was selected. The jump height was calculated by the raising of the body's center of mass between the standing position and the position at the apex of the jump. The location of the center of mass was determined using anthropometric data from Winter,[19] and

Table 1. Injured- and Uninjured-Limb Jump Height, Push-Off Phase Duration, Joint Angles at Takeoff and Total and Maximal Moments During a Single-Legged Jump (Mean ± SD)

Variable	Joint	Injured Limb	Uninjured Limb	*P* Value
Jump height, cm		16 ± 0.06[a]	21 ± 0.04	.001
Push-off phase duration, ms		464 ± 68	465 ± 105	.97
Joint angle at takeoff, °	Hip	160.78 ± 8.43	166 ± 5.60	.11
	Knee	14.82 ± 9.05[a]	2.22 ± 7.54	.009
	Ankle	134.00 ± 8.22[a]	145.79 ± 8.87	.001
Maximal moment, N·m/kg	Total	4.60 ± 0.70[b]	5.34 ± 0.81	.01
	Hip	1.23 ± 0.48	1.52 ± 0.66	.24
	Knee	1.32 ± 0.74	1.60 ± 0.71	.22
	Ankle	2.05 ± 0.84	2.22 ± 0.88	.40

[a] Indicates $P < .01$.
[b] Indicates $P < .05$.

joint angles (hip, knee, and ankle) were calculated from the absolute coordinates of the landmarks. The net moments of the hip, knee, and ankle joints during the POP were calculated using a standard inverse-dynamic procedure. The joint power was equal to the product of the joint moment and the angular joint velocity during the POP. The values of moment and power were normalized by participant body mass. Maximal moments and powers corresponded to the maximal value of the moment and the power for the hip, knee, and ankle joints during the POP. At maximal joint power, the values of the joint moment and the angular joint velocity were reported. Total joint moment and power corresponded to the sum of each maximal moment[16] and power of the lower limb joints. Positive moments and powers were defined as *joint extension*.

Statistical Analyses

All data were analyzed using a 2-factor analysis-of-variance model with lower extremity (IL, UL) as a repeated factor and group (BPTB graft, hamstrings tendon graft) as a between-subjects factor. The α level was set at .05. Effect sizes (Glass Δ) were calculated and reported when we found differences.[21] Statistical analyses were conducted using the distribution free software R (version R.2.7.2; R Foundation for Statistical Computing, Vienna, Austria).

RESULTS

For all data, the analysis of variance revealed no interaction between lower limb and group. In the studied population, we found no effect of surgical technique on functional recovery. We report only the results of the ACL reconstruction independent from the graft location.

Jump height was 24% less in the IL than the UL ($F_{1,9} = 23.3$, $P = .001$, Glass $\Delta = 0.86$). The POP duration was similar in both legs, with a value of 464 ± 68 milliseconds in the IL and 465 ± 105 milliseconds in the UL ($F_{1,9} = 0.0$, $P = .97$; Table 1).

The takeoff joint angle of the hip was not different between the IL and the UL ($F_{1,9} = 2.6$, $P = .11$). We found that knee-joint extension was less at takeoff ($F_{1,9} = 11.4$, $P = .009$, Glass $\Delta = 1.39$), and ankle plantar flexion was less ($F_{1,9} = 22.6$, $P = .001$, Glass $\Delta = 1.43$) in the IL than the UL. All takeoff joint angles are reported in Table 1.

Total moment was 14% less in the IL than the UL ($F_{1,9} = 11.1$, $P = .01$, Glass $\Delta = 1.01$). However, maximal moments were similar for the hip ($F_{1,9} = 0.0$, $P = .24$), knee ($F_{1,9} = 1.8$, $P = .22$), and ankle ($F_{1,9} = 0.8$, $P = .40$) joints between groups (Table 1).

Total power was 35% less in the IL than the UL ($F_{1,9} = 24.2$, $P = .001$, Glass $\Delta = 1.17$). Maximal hip and knee power was not different between groups, with values of 3.19 ± 2.11 W/kg in the IL and 5.56 ± 3.18 W/kg in the UL for the hip joint ($F_{1,9} = 0.1$, $P = .09$) and 3.67 ± 3.02 W/kg in the IL and 5.53 ± 3.79 W/kg in the UL for the knee joint ($F_{1,9} = 1.6$, $P = .24$) (Table 2). Maximal ankle power was 34% less in the IL than the UL ($F_{1,9} = 11.3$, $P = .009$, Glass $\Delta = 0.74$; Figure).

The values of joint moment and angular joint velocity at maximal power for each lower limb joint are reported in Table 2. For the ankle joint, we noted that joint moment was similar ($F_{1,9} = 0.8$, $P = .41$) and angular velocity was 31% less for the IL than the UL ($F_{1,9} = 17.8$, $P = .004$, Glass $\Delta = 2.01$).

Table 2. Injured- and Uninjured Limb Angular Velocity and Moment at Maximal Power in the Hip, Knee, and Ankle Joints

Variable	Joint	Injured Limb	Uninjured Limb	*P* Value
Maximal power, W/kg	Hip	3.19 ± 2.11	5.56 ± 3.18	.09
	Knee	3.67 ± 3.02	5.53 ± 3.79	.24
	Ankle	12.37 ± 8.60[a]	18.72 ± 9.10	.009
Angular velocity, °/s	Hip	200.00 ± 8.22	272.79 ± 8.87	.14
	Knee	204.29 ± 9.05	256.98 ± 7.54	.16
	Ankle	364.30 ± 8.43[a]	526.74 ± 5.60	.004
Joint moment, N·m/kg	Hip	0.84 ± 0.84	1.05 ± 0.88	.45
	Knee	0.95 ± 0.74	1.05 ± 0.71	.61
	Ankle	1.44 ± 0.48	1.57 ± 0.66	.41

[a] Indicates $P < .01$.

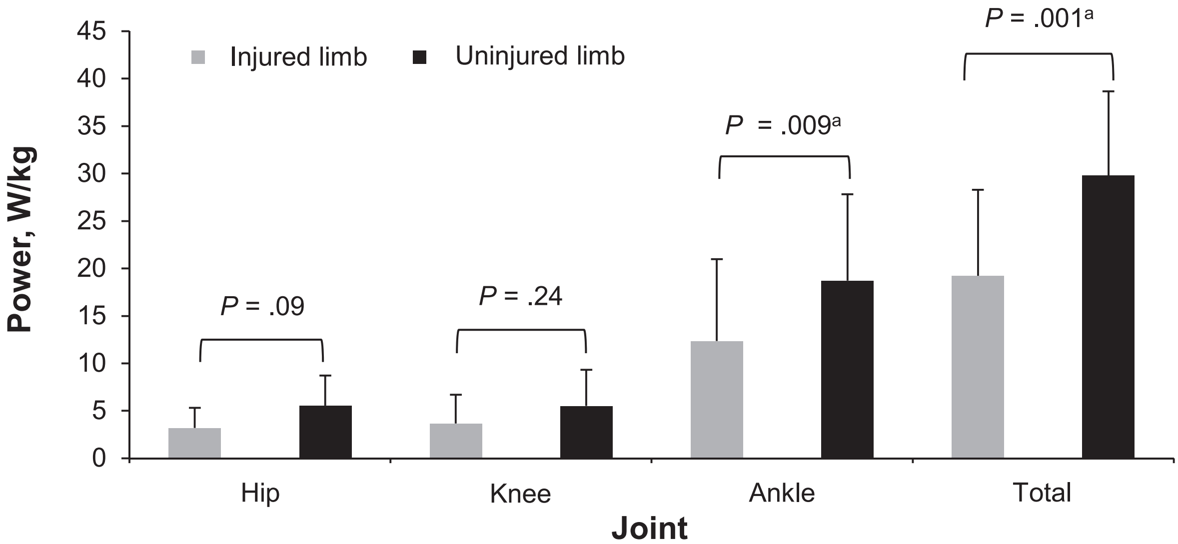

Figure. Maximal power of the hip, knee, and ankle joints in the injured limb and the uninjured limb during the push-off phase of a single-legged squat jump and total power in the injured limb and uninjured limb. [a] Indicates $P < .01$.

DISCUSSION

After ACL reconstruction and when patients were clinically ready to return to sport activities, asymmetry was noted in jump performance. We found jump height was 24% less in the IL than the UL after ACL reconstruction. This decrease confirms the findings of Gustavsson et al,[13] who also observed a 24% decrease during vertical jump after surgery. The release velocity of the body's center of mass at takeoff was reduced; however, we did not find greater POP duration in the IL than the UL. Given that the time to produce force was the same after ACL reconstruction, the capacity to generate the force was reduced. Through the analysis of joint kinematics and kinetics, our discussion aims to identify the articular or muscular variables that are altered after surgery and lead to the decrease in jump height.

Joint Kinematics

After ACL reconstruction, knee-joint extension was less at takeoff in the IL than the UL. We think that a phenomenon of "overprotection" of the knee joint develops after surgery on the IL. Psychological factors, such as the fear of reinjury, have been shown to limit the extent of functional recovery after ACL reconstruction[12,22] and, therefore, may limit knee-joint extension. During dynamic movements and given the anatomic constraint,[23] antagonist muscles play the role of "brakes" against the movement to protect the joint. In this study, we speculate that early contraction of the hamstrings muscles slowed knee-joint extension during the performance of a single-legged jump. We also can suggest that this phenomenon could be related to the deficit in proprioception observed in the knee joint after ACL injury and surgery.[24,25] Katayama et al[25] described a correlation between reduced joint position sense and decreased jumping performance after ACL injury, whereas MacDonald et al[24] observed a higher threshold to detect passive motion of the knee joint in the IL than UL after ACL reconstruction. The reduced knee extension in the IL affects the ankle joint by limiting plantar flexion. The limitation of both the extension of the knee joint and ankle plantar flexion could decrease the vertical energy generation during the POP after ACL reconstruction, leading to a decrease in jumping performance in the IL compared with the UL.

Joint Kinetics

We observed a 14% deficit in total moment but no difference for maximal moments of the hip, knee, and ankle joints between the IL and UL. This result is related to the insignificant difference observed for each maximal joint moment. However, summing the 3 maximal moments amplifies the difference and leads to significance. Given that a moment is mainly the result of muscular forces, we suggest that the global muscular recovery of the lower limb is not complete in the IL after ACL reconstruction. These results contrast with the findings of Ernst et al,[16] who reported equal total moments, decreased maximal knee moment, and no difference for the maximal hip and ankle moments between the IL and UL after ACL reconstruction. The nonstandardization of the testing procedures in their study[16] limits the comparison with our results. Their participants performed a single-legged jump and used their natural jumping techniques with no restriction on countermovement or use of the upper limbs. Motion of the upper limbs can affect the mechanical output of the lower limb joints[26–30] and thereby modify jump performance by increasing the control of balance and changing the orientation of the body at takeoff.[31] Moreover, Ernst et al[16] assessed the stretch-shortening cycle, whereas we focused only on the concentric contraction during the POP of a jump. These differences in methods and testing procedures could explain the variability observed in the results between our studies.

Webster et al[32] analyzed energy dissipation during eccentric contraction through the landing of a vertical jump. They found equal total moments and decreased maximal knee-flexion moment between the IL and UL and no effect of surgical technique (BPTB or hamstrings tendon grafts) on these variables. The difference in the mode of muscular contraction could explain the disparity between their results[32] and ours.

We observed a decrease of 35% in total power that can be explained by the 34% decrease in maximal ankle power between the IL and the UL. By dividing the maximal ankle power into the joint moment and the angular velocity, we demonstrated that the deficit in maximal ankle power does not come from an alteration in joint moment but from a decrease in the angular velocity of ankle plantar flexion. Our results showed that maximal hip and knee power was not different between legs. Our findings contrast with those of Castanharo et al,[17] who observed a decrease in the maximal knee power and similar maximal hip power during a bilateral squat jump. However, they did not measure the total power or maximal ankle power. The different outcomes between their study[17] and ours could be related to the nature of the activity performed. Indeed, different motion strategies are adopted for double-legged and single-legged jumps.[33] Yeow et al[33] noted a greater hip and knee contribution to dissipate energy during a double-legged landing, whereas the hip and ankle dissipated most of the energy during a single-legged landing. Moreover, most ACL injuries occur during landing.[34] It is then that the fear of reinjury could limit the use of the knee joint and decrease knee power at landing.

In our study, kinematic and kinetic data were not different between ACL reconstruction with BPTB and hamstrings tendon grafts. These results are supported by researchers who have shown no differences among graft types used in ACL ligamentoplasty, especially for functional and kinematic outcomes.[1,35–37] Nevertheless, our results cannot be generalized due to the small sample sizes of the 2 subgroups.

The originality of our work is in the way we analyzed maximal joint power; dividing the power into the joint moment and the joint angular velocity allows more accurate identification of the deficit. Rehabilitation, therefore, could be individualized to optimize recovery after ACL ligamentoplasty.

CONCLUSIONS

At 7.3 months after ACL reconstruction, clear kinematic and kinetic alterations were demonstrated in the IL compared with the UL. These modifications led to a decrease in jump height during the performance of a single-legged squat jump. Our study highlights (1) smaller knee-extension and ankle plantar-flexion angles at takeoff, (2) decreases in both total moment and power, and (3) reduced maximal ankle power with decreased angular velocity of ankle plantar flexion.

The main implication of our work is to highlight the importance of expanding the movement analysis. Enhancing the tools for assessing articular and muscular variables during a multijoint movement would help multidisciplinary teams to individualize rehabilitation protocols, restore symmetry between the lower limbs, and improve function after ACL reconstruction.

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Address correspondence to Benoît Pairot de Fontenay, PT, Centre de Recherche et d'Innovation sur le Sport—CRIS—EA 647. UFR STAPS—Université Claude Bernard—Lyon 1, 27–29, Bd du 11 Novembre 1918, 69622 Villeurbanne Cedex, France. Address e-mail to benoit.pdf@gmx.com.