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# Force Production and Reactive Strength Capabilities After Anterior Cruciate Ligament Reconstruction

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***Context:*** Ambiguity exists in the literature regarding whether individuals can restore function to 100% after anterior cruciate ligament (ACL) reconstruction. The response of force production and reactive strength in stretch-shortening cycle activities after surgery has not been established.

***Objective:*** To compare reactive strength and force production capabilities between the involved and uninvolved legs of participants who had undergone ACL reconstruction and rehabilitation with the reactive strength and force production capabilities of a control group.

***Design:*** Repeated measures, cross-sectional.

***Setting:*** Research laboratory.

***Patients or Other Participants:*** Ten participants with ACL reconstructions who had returned to their chosen sports and 10 age-matched and activity-matched control subjects.

***Intervention(s):*** We screened the ACL group with the International Knee Documentation Committee Subjective Knee Evaluation Form and functional performance tests to measure a basic level of function. We assessed force production capabilities and reactive strength using squat, countermovement, drop, and rebound jump protocols on a force sledge apparatus.

***Main Outcome Measure(s):*** The dependent variables were flight time, peak vertical ground reaction force, leg spring stiffness, and reactive strength index.

***Results:*** No participant in the ACL group exhibited functional deficits in comparison with normative values or the control group. Using the force sledge apparatus, we found no notable differences in force production capabilities and reactive strength in the ACL group when comparing the involved with uninvolved legs or the degree of difference between legs with the control group.

***Conclusions:*** After ACL reconstruction, rehabilitated participants did not exhibit deficits in force production or reactive strength capabilities. Our results suggest that force production and reactive strength capabilities can be restored to levels comparable with the uninjured control limb and may not be limiting factors in ACL recovery.

***Key Words:*** knee injuries, leg spring stiffness, functional performance tests, force sledge apparatus

**Key Points**

- No deficits in force production and reactive strength capabilities were identified in limbs that underwent anterior cruciate ligament reconstruction.
- Control of leg spring stiffness was comparable between the limb that had been reconstructed and the contralateral control limb.
- After anterior cruciate ligament reconstruction, individuals can be rehabilitated to high levels of function in stretch-shortening cycle exercise.

Ambiguity exists in the published literature regarding whether or not individuals can restore lower limb function to 100% after anterior cruciate ligament (ACL) reconstruction and subsequent rehabilitation. Postoperatively, despite full rehabilitation programs, ACL-reconstructed (ACL-R) patients can still suffer deficiencies such as decreased proprioception,[1–3] increased muscular latency,[1] decreased strength,[4,5] and decreased functional performance.[6] The findings from these studies suggest that the ACL-R individual cannot be rehabilitated to 100%. However, authors of these studies have not attempted to classify or to exclude participants depending on their level of rehabilitative success. This factor makes it likely that patients with various rehabilitative outcomes could be included in each study. Between-leg imbalances in those with inadequate rehabilitation may result in apparent significant asymmetry for a group in spite of symmetry in well-rehabilitated patients. Aggregation is a statistical effect in which the averaging of group data can mask specific aspects of an individual's performance and result in the false support of hypotheses.[7] Although these authors[1–6,8] have provided important information regarding what types of deficiencies can remain in ACL-R patients even after completion of a postsurgical rehabilitative program, they have not established whether full recovery after surgery is possible. These investigators have examined participants an average of 6 to 18 months postoperatively. A possible rehabilitative effect due to prolonged exposure to the stimulus of competitive sport, therefore, has not been considered.

Our objective was to determine whether rehabilitated ACL-R individuals were left with residual deficits in performance after their rehabilitation programs. Previous researchers[2–6] suggested that some degree of impairment is inevitable in the ACL-R individual despite a positive rehabilitation process. We attempted to test this hypothesis by specifically including participants who could be deemed well rehabilitated and who had returned to full activity in their chosen sports for a prolonged period. For this purpose, the nature of rehabilitation undergone by participants was not the primary concern, only that the individuals had rehabilitated successfully.

We assessed force production capabilities, reactive strength, and leg spring stiffness during jumping activities in the ACL-R limb in comparison with the uninvolved limb as an internal control and with an age-matched and activity-matched external control group. These biomechanical variables were selected for analysis because unlike isokinetic dynamometry, which commonly is used in ACL-R populations, they provide key information regarding stretch-shortening cycle (SSC) function. Also, they provide more extensive information than field tests commonly used with ACL-R individuals. Information on performance outcome is gained, but the analysis presented here also provides more detailed measurements regarding the manner in which that performance is achieved. Analysis during dynamic jumping activity is highly appropriate for individuals involved in speed and power sports, because this allows for observation of movement behavior in a dynamic manner, similar to the sporting environment in which ACL rupture commonly occurs. This experimental approach could provide insight into the degree to which these specific measures of lower limb function can be restored after reconstruction, rehabilitation, and return to sport and whether they may be a limiting factor to full recovery.

## METHODS

### Participants

Ten adults with a history of 1 ACL reconstruction (8 men, 2 women; age = 23.8 ± 6 years, height = 176.5 ± 7 cm, mass = 79 ± 14 kg) were recruited for participation in this research study (ACL-R group). Ten age-matched and activity-matched volunteers (8 men, 2 women; age = 23.3 ± 3.1 years, height = 175.4 ± 7 cm, mass = 77.3 ± 8 kg) served as a control group (CON group). Participants recruited for the ACL-R group had ACL reconstruction performed with arthroscopically assisted techniques; 4 of 10 reconstructions used a hamstring tendon autograft and 6, a patellar tendon autograft. The mean time from surgery was 27.0 ± 14.5 months. Recruits were participants in a variety of field sports involving large sprinting, cutting, and jumping components (such as rugby and soccer). The study was approved by the university's Research Ethics Committee, and all volunteers signed an informed consent form before participating.

### Criteria for Participation

The ACL-R group volunteers were recruited through contact with local physiotherapists. Contacted physiotherapists were asked to refer past patients who met the following criteria: (1) only 1 surgery for a rupture of the ACL; (2) presented to the attending physiotherapist without any symptoms of significant disruption to the structures surrounding the ACL, such as the joint capsule, medial or lateral meniscus, posterior cruciate ligament, or medial or lateral collateral ligament; (3) no history of reinjury to the ACL-R knee after surgery; (4) no history of surgery or traumatic injury to the contralateral knee; (5) no history of any surgery or injury to the hips, knees, or ankles of either leg within the last 6 months that caused an inability to bear weight or a significant limp for 1 to 2 days; (6) at least 12 months postsurgery. All ACL-R group volunteers underwent a formal rehabilitation program postsurgery and were cleared to return to full physical activity by their attending physiotherapists. However, standardization of these rehabilitation programs was not possible. Participants were screened with the International Knee Documentation Committee (IKDC) Subjective Knee Evaluation Form[9] and with functional performance tests (FPTs). Participants scoring below established norms in these tests were not deemed sufficiently rehabilitated and were excluded from the study. Two potential volunteers were excluded from participation through these screening tools.

Participants in the CON group were matched with the ACL-R group for age, sex, and mass as closely as possible. Those in the CON group were active in the same sports as those in the ACL-R group. Participants were assigned to the CON group if they met the following additional criteria: (1) no history of any injury to the ACL, (2) no previous history of surgical repair of any lower limb condition, (3) no history of any surgery or injury to the hips, knees, or ankles of either leg within the last 6 months that caused an inability to bear weight or a significant limp for 1 to 2 days.

### Testing Procedures

Participants reported to the biomechanics research laboratory for 1 testing session for a total test time of 1 hour. Volunteers first completed a Physical Activity Readiness Questionnaire (Canadian Society for Exercise Physiology, Gloucester, Ontario, Canada) and provided written informed consent to participate in the study. The CON group participants were asked to identify their dominant leg. Consistent with the task demands of this experimental study, the dominant leg was identified as the preferred jumping leg.

### International Knee Documentation Committee Subjective Knee Evaluation Form

We administered the IKDC Subjective Knee Evaluation Form to the ACL-R group. This is a Likert-scale questionnaire developed by a committee of international knee experts in 1987 as a standardized documentation system.[9] It is an evaluative measure to detect improvement or deterioration in symptoms, function, and sports activity experienced by patients with a variety of knee conditions, including ligamentous injuries.[9]

We used normative data collected by Anderson et al[10] to interpret collected IKDC scores. We converted the subjects' scores on this questionnaire to a standard score ($z$), which relates the individual's result to the population mean and SD for the patient's age and sex. We calculated the standard score for each subject as follows:

$$z = (\text{patient's IKDC Subjective Knee Form score} - \text{mean score for age and sex group}) \div (\text{SD for age and sex group})$$

We did not administer the IKDC form to the CON group.

### Functional Performance Testing

Functional performance tests are often used by rehabilitation professionals and researchers to evaluate when an

**Figure 1. The force sledge apparatus.**

athlete can safely return to unrestricted sporting activities.[5,6,11,12] These FPT measures are popular for administration to ACL-R athletes due to their ability to objectively quantify lower limb function.

All subjects performed 2 FPTs: the single-leg hop-for-distance test and the 6-m timed hop test. The first FPT to be performed and the first extremity to be tested were chosen randomly. Both FPTs were performed 3 times on each leg.

For the single-leg hop-for-distance test, we instructed the participant to jump as far forward as possible on the selected leg from a predetermined line, to land on the same leg, and to maintain balance. When the participant could not maintain balance, the trial was disregarded and repeated. The greatest distance of the 3 tests was recorded in centimeters and was used as the dependent score.

For the 6-m timed hop test, we instructed the participant to hop repeatedly on the selected leg over the course of a predetermined 6-m distance. The shortest time of the 3 tests was recorded in seconds, by handheld stopwatch, and was used as the dependent score. When performing both FPTs, participants clasped their hands behind their backs, so their arms could not contribute to the jumping action.

Participants were afforded 2 practice attempts for each test and were allowed 30 seconds of recovery between trials. A 1-minute recovery time was permitted between tests. This protocol allowed for the collection of 3 usable trials for each participant.

We used the participant's best score for each leg in each test to calculate the leg symmetry index (LSI) for both tests. In the ACL-R group, this was achieved by dividing the score for the involved leg by the score for the uninvolved leg and in the CON group by dividing the score for the nondominant leg by the score for the dominant leg. The best score, as opposed to the average score, was chosen based on recommendations made by Clark.[12] We then averaged the scores for each test to establish a combined LSI. In the ACL-R group, the LSI was calculated as the best score achieved with the involved leg as a percentage of the best score achieved with the uninvolved leg. In the CON group, the LSI was calculated as the best score achieved with the nondominant leg as a percentage of the best score achieved with the dominant leg.

## Force Sledge Apparatus Testing

The force sledge apparatus (Figure 1) has been developed to measure external kinetic output and to quantify the mechanical properties of the musculoskeletal structures of the lower limb during dynamic exercise. The force sledge consists of a sledge with attached chair, sliding on a fixed track inclined at 30° to the horizontal. A winch with a quick pull-release mechanism is located at the top of the track. This can be attached to the sledge and used to hoist subjects to desired heights for dropping. A force platform (model OR6-5; AMTI, Watertown, MA) is positioned at right angles to the base of the track. The sledge allows for isolation of the joint actions of interest and minimizes the contribution of extraneous factors, such as arm swing. The apparatus provides reliable control of eccentric loadings with high agreement between measured impact velocity and predicted velocity based on the dropping height ($r = .996$).[13]

The sledge also allows the jumping activity to take place in a safe, controlled environment. Due to the mechanical construct of the sledge, movement of the body's center of mass is only allowed in the sagittal plane. Movement in the frontal or transverse plane is not facilitated. Consequently, lateral movements of the lower limbs are minimized, and twisting force moments that can be a causative factor in ACL injury are reduced.

All participants performed 4 testing protocols in the force sledge apparatus: the squat jump (SJ), countermovement jump (CMJ), drop jump (DJ), and rebound jump (RBJ). All jumps were single legged, and the protocols were performed on both legs in a randomized order. For all 4 protocols, the participants were seated, secured to the chair with a harness around the waist and straps over their shoulders, and instructed to fold their arms across their chest to minimize upper body movement during the jumps. We instructed participants to apply maximum effort when performing all jumps. One minute of recovery was provided between trials in the SJ, CMJ, and DJ protocol. Two minutes of recovery were provided between the 4 tests of that protocol.

## Squat Jump

Participants were given a visual demonstration of the appropriate jumping action. While seated in the force sledge apparatus, a participant placed his or her foot flat on the force plate. This foot placement was marked to ensure consistency in starting position among trials. We identified the bony prominences of the greater trochanter, lateral epicondyle, and ankle through palpation. A goniometer was used to determine a 90° angle of knee flexion, and the position of the sledge chair at this angle was marked. With the starting foot position held consistent, this mark allowed us to move participants into a position of 90° of knee flexion in each trial without having to remeasure the angle with the goniometer.

Before each jump, participants placed a foot on the marked plate and, with our assistance and verbal feedback, lowered themselves to the position of 90° of knee flexion. We instructed the participants to hold this starting position steady before driving themselves into the air, without any prestretch of the musculature, with maximal effort. Before the first trial and between subsequent trials, we emphasized the need to drive themselves straight upward and to use no prestretch. Participants were allowed 2 practice jumps before performing 3 jumps on each leg for which data were recorded. The SJ involves purely concentric contraction of the leg extensors, with no SSC.

### Countermovement Jump

Participants were given a visual demonstration of the CMJ jumping action. Seated in the force sledge apparatus, they positioned the foot between the same markings used in the SJ protocol and extended the leg. The starting position for the CMJ was identical to that of the SJ but with the leg extended.

From this starting position, participants were instructed to jump as high as possible. No instruction was given regarding the specific extent to which they should use the countermovement (ie, they were not instructed to use a shallow or deep prestretch). Participants were afforded 2 practice jumps before performing 3 jumps on each leg for which data were recorded. The CMJ is a maximal-effort jump that uses the SSC.

### Drop Jump

Participants were given a visual demonstration of the DJ procedure. They began the jumps seated in the force sledge apparatus with their feet on the force plate. With prior warning, they were winched up to a predetermined drop height 0.30 m above the force plate, along the sledge's inclined track. We provided the participants with a 3-2-1 countdown, after which the winch mechanism was released and they were dropped toward the force plate. We instructed them to land with the legs toward extension and to jump rapidly off the plate upon landing. We stressed consistently between trials that participants should minimize their ground contact time and jump as high as possible. Previous researchers[14] have shown that verbal instruction can influence the jumping performance. Participants were allowed 2 practice jumps before performing 3 jumps on each leg for which data were recorded. The DJ is a maximal-effort jump, following a drop for a fixed height, using a single SSC.

### Rebound Jump

Participants were given a visual demonstration of the procedure. As in the DJ procedure, they began the jumps seated in the force sledge apparatus, with their feet on the force plate. With prior warning, they were winched up to a predetermined drop height 0.30 m above the force plate, along the sledge's inclined track. This starting position is an identical position to that used in the DJ. We provided participants with a 3-2-1 countdown, after which the winch mechanism was released and they were dropped toward the force plate. We instructed them to land with their legs toward extension and, upon landing, to perform 4 maximal jumps in quick succession. For all jumps, we stressed that participants should minimize their ground contact time and jump as high as possible. Because each jump in the RBJ protocol was performed in quick succession, there was no rest interval between the 3 trials.

The first jump of this set of 4 was considered a drop jump; the following 3 jumps were the RBJs. Participants were allowed practice sets of 4 jumps before performing 1 set of 4 on each leg for which data were recorded. The RBJ is a series of repeated, maximal-effort jumps using repeated shortening cycles. The RBJ also can be considered maximal-effort hopping.

### Data Collection

Ground reaction force measurements were obtained for all jumps using the force plate, which sampled at 1000 Hz. For each trial, collected force data were exported to the Microsoft Excel software program (version 9.0.6926; Microsoft Corp, Redmond, WA) and were graphed with respect to time. A reflective marker was attached to the sledge, and sagittal-plane Super VHS video recordings (50 Hz) were obtained. Affine scaling technique was used to calibrate the camera view space. The affine scale aids in controlling for camera tilt and offset from center. The video recordings were digitized using Peak Motus (Peak Performance Technologies, Inc, Englewood, CO), and the displacement of the sledge was calculated during the DJ and RBJ. Instances of initial foot contact, full crouch depth, takeoff, and landing were identified, where appropriate, using the acquired video footage and ground reaction force traces.

In the SJ and CMJ, the derived variables were flight time (FT) and peak ground reaction force ($Fy_{peak}$). In the DJ and RBJ, the derived variables were FT, $Fy_{peak}$, contact time (CT), displacement of the leg spring ($\Delta L$), vertical leg spring stiffness ($K_{VERT}$), and reactive strength index (RSI).

The FT was calculated as the time between takeoff and landing. The CT was defined as the time between initial foot contact and takeoff. The $\Delta L$ was calculated as the displacement of the sledge from the point of initial foot contact and full crouch depth. A spring mass model was used to analyze $K_{VERT}$, which was defined as the ratio of $Fy_{peak}$ to $\Delta L$ at the instant the leg spring was maximally compressed. The $Fy_{peak}$ and $\Delta L$ occurred simultaneously during hopping or running.[15] The RSI represents an ability to change quickly from an eccentric to a concentric contraction.[16] In the derivation of RSI, an intermediate calculation of jump height was first needed. Considering the 30° inclination of the force sledge apparatus, jump height was approximated as $(9.81 \times FT^2)/16$. The RSI was then calculated as the height jumped divided by CT.

### Statistical Analyses

All statistical analyses of the data were carried out in SPSS (version 13.0.1; SPSS Inc, Chicago, IL). The LSI between the ACL-R and CON groups was compared using a 2-tailed, independent-samples *t* test with a significance level of .05. Reliability of the dependent variables measured with the force sledge apparatus was assessed using the Cronbach $\alpha$ reliability coefficient and intraclass correlation coefficients (ICCs) with a 2-way mixed model to absolute agreement for both single and average measures. Comparative analysis of the force sledge apparatus testing results, between the involved and uninvolved legs in the ACL-R group, was conducted using a general linear model analysis of variance with repeated measures. The model had 2 within-subjects factors: leg (with 2 levels: involved leg, uninvolved leg) and trial (with 3 levels).

The analyzed dependent variables were FT, $FY_{peak}$, $K_{VERT}$, and RSI. The model included all interaction terms. A significance level of .05 was used.

Table 1. Group Interaction for Leg Symmetry Index (%)[a]

| Group | Single-Leg Hop-for-Distance Test, % | 6-m Timed Hop Test, % | Combined Leg Symmetry Index, % |
|---|---|---|---|
| Anterior cruciate ligament reconstruction (n = 10) | 98.3 ± 8.0 | 97.8 ± 8.9 | 97.6 ± 6.4 |
| Control (n = 10) | 96.4 ± 5.1 | 99.2 ± 9.1 | 97.8 ± 5.9 |

[a] No differences observed ($P > .5$).

Between-leg differences in the ACL-R group were compared with those of the CON group. The difference between the ACL-R group's involved and uninvolved leg results was compared with the difference between the dominant and nondominant leg results in the CON group. The mean scores for all recorded dependent variables were calculated for the uninvolved leg of each participant in the ACL-R group and the dominant leg of each participant in the CON group. This mean score was considered each participant's baseline level of performance. Participants' scores for each trial on the involved leg or nondominant leg then were subtracted from this baseline to demonstrate the degree of between-legs difference. Differences between the baseline scores and the involved leg or nondominant leg scores were evaluated between groups using a general linear model analysis of variance with repeated measures. The analysis of variance had 2 within-subjects factors: group (with 2 levels: experimental, control) and trial (with 3 levels).

Effect sizes were obtained for the analysis of variance using partial eta squared ($\eta_p^2$), which is defined as follows[17]: $\eta_p^2 = SS_{effect}/(SS_{effect} + SS_{error})$ where $SS_{effect}$ is the effect variance and $SS_{error}$ is the error variance. For the independent-samples *t* tests, effect size was calculated using the Cohen d, which is defined as follows[18]: $d = M_1 - M_2/\sigma_{pooled}$ where $M_1$ is the mean of group 1, $M_2$ is the mean of group 2, and $\sigma_{pooled}$ is the pooled SD.

## RESULTS

### International Knee Documentation Committee Subjective Knee Evaluation Form

The IKDC score represents the score for the participant's involved leg, whereas the mean normative score is derived from the data of Anderson et al[10] for age-related and sex-related participants from the total group, including those with a history of knee conditions, treatment, and surgery. The ACL-R participants scored, on average, 5.6% higher and 0.26 SD above the population mean (*z* score) of the reported normative data for a combined group of previously injured and uninjured individuals.

Table 1 presents data from the administered FPTs for both the ACL-R and CON groups. Examination of participants' scores on an individual basis revealed that no one in the ACL-R group presented with a combined LSI of less than 85%, the threshold above which 90% of a normal, uninjured population scores as reported by Barber et al.[19] In the ACL-R group, the mean score was 97.6%, with a range from 88.7% to 108.1%. In the CON group, all participants presented in the upper 90th percentile, according to the data of Barber et al.[19] The mean score in the CON group was 97.8%, with a range from 87.3% to 104.5%.

Table 2. Reliability Data for All Measured Variables Using the Force Sledge Apparatus[a]

| | Flight Time | | | Peak Ground Reaction Force ($Fy_{peak}$) | | | Vertical Leg Spring Stiffness ($K_{VERT}$)[b] | | | Reactive Strength Index[b] | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Cronbach α | Intraclass Correlation Coefficient, Single Measures | Intraclass Correlation Coefficient, Average Measures | Cronbach α | Intraclass Correlation Coefficient, Single Measures | Intraclass Correlation Coefficient, Average Measures | Cronbach α | Intraclass Correlation Coefficient, Single Measures | Intraclass Correlation Coefficient, Average Measures | Cronbach α | Intraclass Correlation Coefficient, Single Measures | Intraclass Correlation Coefficient, Average Measures |
| Squat jump | .98 | .93 | .98 | .99 | .98 | .99 | | | | | | |
| Countermovement jump | .98 | .95 | .98 | .98 | .93 | .97 | | | | | | |
| Drop jump | .96 | .88 | .96 | .98 | .89 | .98 | .96 | .89 | .96 | .96 | .89 | .96 |
| Rebound jump | .98 | .93 | .98 | .97 | .95 | .97 | .97 | .92 | .97 | .98 | .95 | .98 |

[a] Data represent all jumps on the uninvolved leg of the anterior cruciate ligament-reconstruction group and the dominant leg of the control group (n = 20).
[b] Vertical leg spring stiffness and reactive strength index were calculated only in the drop jump and rebound jump protocols.

Table 3. Flight Time (FT, s) and Peak Ground Reaction Force ($Fy_{peak}$, N) for the Jump Protocols in the Anterior Cruciate Ligament-Reconstruction Group (Mean ± SD)

| Protocol | | Uninvolved Leg | Involved Leg |
|---|---|---|---|
| Squat jump | FT | 0.616 ± 0.05 | 0.615 ± 0.06 |
| | $Fy_{peak}$ | 1153 ± 183 | 1110 ± 209[a] |
| Countermovement jump | FT | 0.656 ± 0.06 | 0.655 ± 0.07 |
| | $Fy_{peak}$ | 1136 ± 196 | 1108 ± 198 |
| Drop jump | FT | 0.674 ± 0.06 | 0.675 ± 0.08 |
| | $Fy_{peak}$ | 1376 ± 233 | 1357 ± 308 |
| Rebound jump | FT | 0.684 ± 0.06 | 0.673 ± 0.08 |
| | $Fy_{peak}$ | 1611 ± 346 | 1577 ± 411 |

[a] Difference between involved and uninvolved legs ($P$ = .041).

Statistical analysis revealed no difference and low effect sizes in LSI between the ACL-R and CON groups as measured in the single-leg hop-for-distance test ($P$ = .71, d = 0.29), the 6-m timed hop test ($P$ = .74, d = 0.16), or the combined LSI score ($P$ = .93, d = 0.042).

## Force Sledge Apparatus Testing

Table 2 demonstrates the trial-to-trial reliability of the collected data using the force sledge apparatus. Three trials of each measured variable were analyzed for the dominant leg of the CON group and the uninvolved leg of the ACL-R group, representing a total group of 20. The Cronbach α reliability coefficient and both single and average ICCs for each dependent variable are presented.

First, we assessed lower limb performance of the ACL-R group's involved legs in comparison with their own uninvolved legs, the internal control. Next, we statistically compared the degree of difference between the involved and uninvolved legs of the ACL-R group with the degree of difference between the dominant and nondominant legs of the external CON group.

Table 3 presents the FT and $Fy_{peak}$ data for the SJ, CMJ, DJ, and RBJ protocols for the ACL-R group. We observed a significant difference in $Fy_{peak}$ between legs in the SJ, with the ACL-R participants generating more force on the uninvolved leg than on the involved leg ($P$ = .041, $\eta_p^2 = 0.386$). This lower generation of force did not affect performance outcome on the involved leg, however, with the ACL-R participants producing highly comparable flight times in both the uninvolved and involved legs (0.616 and 0.615 seconds, respectively).

We detected no differences between the involved and uninvolved legs in either FT or $Fy_{peak}$ in any of the jumping protocols of the CMJ, DJ, or RBJ, which required participants to use an SSC ($P \geq .05$, $\eta_p^2 \leq 0.255$ in all cases).

Figure 2 displays RSI and $K_{VERT}$ for both legs during the DJ and RBJ. Again, we observed no differences and low effect sizes between legs in both dependent variables in both protocols ($P \geq .05$, $\eta_p^2 \leq 0.095$ in all cases). Participants had comparable control of leg spring stiffness and could rapidly generate similar levels of impulse in both legs.

Tables 4 through 7 present the measured between-legs differences in the ACL-R and CON groups. A negative value represents a deficit in the involved leg compared with the uninvolved leg in the ACL-R group or a deficit in the nondominant leg compared with the dominant leg in the CON group. A positive value indicates a deficit in the uninvolved leg compared with the involved leg in the ACL-R group or a deficit in the dominant leg compared with the nondominant leg in the CON group.

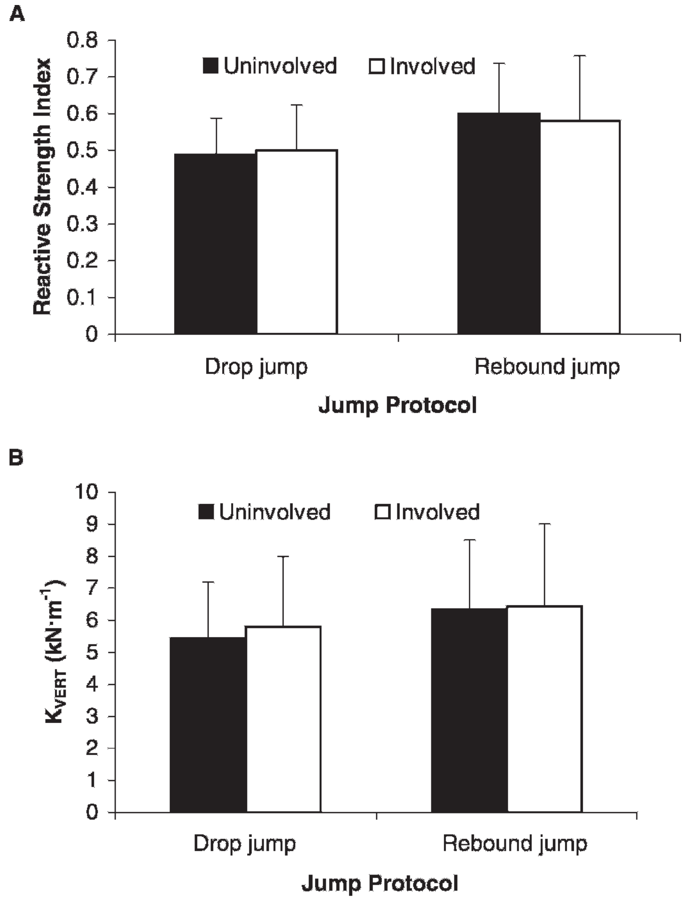


**Figure 2. A, Reactive strength index. B, Vertical leg spring stiffness ($K_{VERT}$) during the drop jump and rebound jump protocols in the anterior cruciate ligament-reconstruction group (mean ± SD). No differences observed between the involved and uninvolved legs.**

These data demonstrate highly comparable degrees of between-legs differences in performance between the ACL-R group and the matched external CON group. We identified no differences between groups ($P > .05$), and we observed small effect sizes ($\eta_p^2 \leq 0.245$) in the comparison of all dependent variables.

## DISCUSSION

The IKDC Subjective Knee Evaluation Form and FPTs are commonly used tools in the clinical setting when assessing the ACL-R individual's rehabilitative progress

Table 4. Between-Legs Differences in Flight Time and Peak Ground Reaction Force for the Squat Jump in the Anterior Cruciate Ligament-Reconstruction and Control Groups (Mean ± SD)

| | Anterior Cruciate Ligament-Reconstruction Group | Control Group | $P$ | $\eta_p^2$ |
|---|---|---|---|---|
| Flight time (s) | −0.001 ± 0.03 | −0.005 ± 0.03 | .757 | 0.011 |
| Peak ground reaction force (N) | −42 ± 57 | −13 ± 62 | .369 | 0.091 |

Table 5. Between-Legs Differences in Flight Time and Peak Ground Reaction Force for the Countermovement Jump in the Anterior Cruciate Ligament-Reconstruction and Control Groups (Mean ± SD)

| | Anterior Cruciate Ligament-Reconstruction Group | Control Group | *P* | $\eta_p^2$ |
|---|---|---|---|---|
| Flight time (s) | −0.001 ± 0.03 | −0.002 ± 0.03 | .950 | 0.000 |
| Peak ground reaction force (N) | −27 ± 60 | 19 ± 90 | .172 | 0.196 |

and ability to return safely to full levels of activity. The ACL-R group scored above established normative means for a comparable population on the IKDC form.

All subjects in the ACL-R group exhibited functional performance symmetry between legs in comparison with normative data established in the literature[19] and in comparison with the CON group. Results of our administered FPTs are in contrast to those of Mattacola et al,[6] who found ACL-R individuals' hops were shorter on the involved leg in the single-leg hop-for-distance test. Methodologic factors may account for this noted difference in findings. Our study included participants who were 27 ± 14.5 months postsurgery, whereas those of Mattacola et al[6] were 18 ± 10 months postsurgery. We specifically included highly rehabilitated individuals who scored well in comparison with established norms on the IKDC Subjective Knee Evaluation Form; to our knowledge, Mattacola et al[6] did not have such an inclusion criterion. Also, our between-legs functional performance analysis used 2 FPTs, in comparison with the single FPT used by Mattacola et al.[6] Two FPTs have been recommended in assessment, because a single FPT used in isolation can have low sensitivity.[20]

An ACL rupture can result in dropping out from competitive sports.[21] Given the results on the IKDC Subjective Knee Evaluation Form and FPTs and the return of all participants to competitive activity in their chosen sporting endeavors, we believe our cohort of ACL-R subjects can be classified as successful rehabilitators.

The force sledge apparatus testing procedures also demonstrated that the SSC function of the ACL-R group was well rehabilitated and suggest that after ACL reconstruction, over time, individuals can return their between-legs force production and reactive strength capabilities to a high level of symmetry. We observed strong between-legs symmetry in all but one of the variables measured on the force sledge apparatus in the ACL-R group. The ACL-R subjects exhibited highly similar performance outcomes in both legs on all 4 jumping tasks (SJ, CMJ, DJ, and RBJ) as measured through the dependent variable of flight time (which is directly related to the height jumped). We detected no differences in $Fy_{peak}$ in any of the jumping protocols that required participants to use an SSC (CMJ, DJ, or RBJ). Our data demonstrated that these participants, despite a history of ACL rupture and surgical repair, could jump to comparable heights with both legs and could generate highly similar levels of ground reaction force during jumps using the SSC.

Table 6. Between-Legs Differences in Flight Time, Peak Ground Reaction Force, Vertical Leg Spring Stiffness, and Reactive Strength Index for the Drop Jump in the Anterior Cruciate Ligament-Reconstruction and Control Groups (Mean ± SD)

| | Anterior Cruciate Ligament-Reconstruction Group | Control Group | *P* | $\eta_p^2$ |
|---|---|---|---|---|
| Flight time (s) | 0.001 ± 0.03 | −0.014 ± 0.03 | .310 | 0.114 |
| Peak ground reaction force (N) | −18 ± 155 | −9 ± 156 | .881 | 0.003 |
| Vertical leg spring stiffness (kN · m−1) | 0.35 ± 1.3 | −0.40 ± 1.8 | .247 | 0.146 |
| Reactive strength index | 0.01 ± 0.08 | −0.03 ± 0.07 | .122 | 0.245 |

Table 7. Between-Legs Differences in Flight Time, Peak Ground Reaction Force, Vertical Leg Spring Stiffness, and Reactive Strength Index for the Rebound Jump in the Anterior Cruciate Ligament-Reconstruction and Control Groups (Mean ± SD)

| | Anterior Cruciate Ligament-Reconstruction Group | Control Group | *P* | $\eta_p^2$ |
|---|---|---|---|---|
| Flight time (s) | −0.01 ± 0.04 | −0.02 ± 0.04 | .533 | 0.045 |
| Peak ground reaction force (N) | −34 ± 96 | −5 ± 223 | .725 | 0.014 |
| Vertical leg spring stiffness (kN · m−1) | 0.08 ± 1.01 | −0.26 ± 1.7 | .602 | 0.031 |
| Reactive strength index | −0.02 ± 0.08 | −0.04 ± 0.11 | .692 | 0.018 |

The participants also demonstrated comparable control of leg spring stiffness in both legs for the DJ and RBJ protocols. Leg spring stiffness represents an integration of the stiffness of all lower limb musculoskeletal structures (including muscles, tendons, and ligaments acting across joints) during locomotion[22] and describes those structures' ability to interact in unison in a spring-like fashion. Muscle and joint stiffness play a key role in functional joint stability.[23] Stiffer muscles resist sudden joint displacements more quickly and more effectively, serving as a protective mechanism against acute knee injury. The direct relationship between leg spring stiffness and lower limb injury is not well established, but too low a level of leg spring stiffness may be associated with excessive joint motion and may lead to soft tissue injury.[24] However, an excessive level of leg spring stiffness can increase shock to the lower extremity, increasing peak joint forces and loading rates, which can contribute to a greater risk for bony injuries such as knee osteoarthritis and stress fractures.[24] Additionally, evidence is strong that the amount of stiffness in a human system is related directly to aspects of athletic performance such as force output,[25] running velocity,[26,27] and running economy.[22] Thus, an optimal level of stiffness ensures an adequate level of performance combined with a protective mechanism against injury. The magnitude of such an optimal level of stiffness has not been established in the literature, but the degree of stiffness should be symmetrical between the ACL-R leg and the uninjured control limb. Symmetrical representation of leg spring stiffness in the ACL-R group is, therefore, a highly positive outcome in this study, both from a performance perspective and also possibly in relation to a decreased risk of reinjury.

Participants also performed these DJ and RBJ protocols in a similarly explosive manner on both the involved and uninvolved legs, with no differences observed in the measure of RSI. The RSI defines the participant's ability to change quickly from an eccentric to a concentric contraction[16] and can be deemed a measure of an individual's "explosiveness." Between-legs imbalances in RSI represent a weakness that would inhibit optimal sporting performance. From a performance perspective, between-legs balance in the ACL-R group in the RSI measure is a favorable outcome.

Our examination of the degree of difference in each dependent variable between the involved and uninvolved legs of the ACL-R group and the dominant and nondominant legs of the CON group revealed no differences. The magnitude of difference between legs in the ACL-R group was comparable with those observed in a similar control population with no previous history of ACL reconstruction, again highlighting the positive outcome of these patients' surgery and subsequent rehabilitation.

Only in the measure of $Fy_{peak}$ did we observe a between-legs difference in the ACL-R group. In the SJ protocol, the involved leg produced less force than the uninvolved leg, generating a mean maximum of 1153 N compared with 1110 N. But despite a statistically significant difference being found ($P = .041$), the actual difference between the involved and uninvolved legs was just 3.7% with a low observed effect size ($\eta_p^2 = 0.386$). This finding did not translate to a performance deficit in the SJ, for no difference was observed between legs in the measure of FT. Also, the degree of difference in $Fy_{peak}$ between legs in the ACL-R group was not different from that in the CON group. Given these factors, we consider the between-legs difference in $Fy_{peak}$ observed in the ACL-R group an unimportant finding.

The lack of differences observed between the involved and uninvolved legs of the ACL-R group does not suggest a lack of sensitivity in our measurement procedures. Strong trial-to-trial reliability was demonstrated in all measured variables, with all $\alpha$ values greater than .96, all single ICC values more than .88, and all average ICC values more than .96 (Table 2). This high observed reliability for all dependent variables indicates that the lack of difference observed between legs in the ACL-R group is true. The reliability coefficients we present are highly similar to those demonstrated in the literature using the same protocols and instrumentation.[28] Because our sample size was larger (n = 20 versus n = 10), our results represent a more accurate estimation of trial-to-trial reliability. Morrow and Jackson[29] showed that as sample size increases, estimates of population reliability become more stable.

Furthermore, the same apparatus and procedures have been used to detect small but significant differences between the dominant and nondominant legs of healthy individuals in a previous study.[28] We are confident that if residual deficits in force production and reactive strength capabilities existed in this ACL-R population, our testing measures would have detected them.

Our findings are contrary to those of previous researchers,[2,7,30] who suggested that, due to postreconstructive deficits in proprioception, function is not entirely restored to the limbs of ACL-R individuals. We postulate a number of reasons as to why our study had such positive findings.

First, participants in our ACL-R group were tested, on average, 27 months postsurgery. Bonfim et al,[1] MacDonald et al,[3] and Keays et al[5] examined participants at means of 6, 18, and 24 months after surgery, respectively, and demonstrated postoperative deficits in knee function. With the extended duration after surgical repair afforded our ACL-R group, the involved leg may have been exposed to a longer training stimulus, which could have contributed to the performance we observed. Also, all participants in our ACL-R group had returned to full activity in their chosen sporting discipline. Prolonged exposure to such activity likely resulted in performance-enhancing effects on the force production and reactive strength capacities of the lower limbs and successfully transferred to the demands of the force sledge protocols we used. Furthermore, participants who scored poorly on the IKDC Subjective Knee Evaluation Form or FPTs were excluded from this study, whereas previous researchers did not make a deliberate effort to exclude poorly rehabilitated individuals. The inclusion of such individuals could aggregate group data against expressions of full recovery in well-rehabilitated patients.

Another possible contributing factor relates to the role of the ACL in proprioception. The sensory system of the cruciate ligaments, along with mechanoreceptors located in other structures of the knee, such as the joint capsule, medial meniscus, and medial collateral ligament, significantly contributes to the functional stability of the knee joint.[3,30] Sensory deficits may persist when the ACL is damaged and is replaced with a graft source, because many of the original mechanoreceptors and nervous connections cannot be restored.[2] Without the normal integration of these processes, a person may be unable to perform physical activity in an efficient manner.[6,30] However, it has been suggested that the grafted ACL can, over time, become reinnervated postreconstruction.[1,31] Our participants were provided with a longer recovery period than those in other studies,[1,3,5] making it possible that the contribution of the ACL to afferent feedback was greater in our ACL-R group, which may have positively affected measures of performance.

It should be noted, however, that we did not directly measure proprioceptive function, for participants were allowed full auditory and visual capabilities. Furthermore, due to the mechanical construct of the sledge, movement of the body's center of mass was allowed only in the sagittal plane; movement in the frontal or transverse plane was not facilitated. The force sledge apparatus reduces the degrees of freedom involved in a jumping task when compared with a jumping task performed in an open environment. Thus, the force sledge can be considered to reduce the coordination and balance demands of a jumping task. We cannot, therefore, discount the possibility that in a task that taxes the balance and coordination abilities of the participants to a greater degree than the force sledge apparatus, such favorable levels of between-legs symmetry in reactive strength and force production would be observed. However, by examining a task that minimizes the contribution of balance and coordination, we have demonstrated that the force production and reactive strength capabilities can be restored to high levels in those recovering from ACL rupture and surgical repair.

One potential limitation of the study, which should be noted, is the combined group of 8 men and 2 women. Such a small cohort of female participants did not allow for a cross-sex comparison of results. This combined group may then aggregate the data in favor of the male population, and findings should not be interpreted as definitively representative of the female population.

## CONCLUSIONS

We deemed the ACL-R group in this study rehabilitated individuals due to their return to participation in their chosen sporting activities, their high scores on the IKDC Subjective Knee Evaluation Form, and their strong between-legs symmetry in FPTs. After ACL reconstruction (27.0 ± 14.5 months), these participants did not exhibit residual deficits in force production or reactive strength capabilities when tested on the force sledge apparatus in dynamic jumping activity. The force sledge apparatus does reduce the coordination and balance demands of the task, and such between-legs symmetry may not be observed in tasks that place more of a proprioceptive demand on the ACL-R individual. However, our results suggest that force production and reactive strength capabilities in jumping tasks were restored postoperatively to a high level of between-legs symmetry after ACL reconstruction in these participants.

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## REFERENCES

1. Bonfim TR, Jansen Paccola CA, Barela JA. Proprioceptive and behavior impairments in individuals with anterior cruciate ligament reconstructed knees. *Arch Phys Med Rehabil*. 2003;84(8):1217–1223.
2. Lephart SM, Kocher MS, Fu FH, Borsa PA, Harner CD. Proprioception following anterior cruciate ligament reconstruction. *J Sport Rehabil*. 1992;1(3):188–196.
3. MacDonald PB, Hedden D, Pacin O, Sutherland K. Proprioception in anterior cruciate ligament-deficient and reconstructed knees. *Am J Sports Med*. 1996;24(6):774–778.
4. Beard DJ, Anderson JL, Davies S, Price AJ, Dodd CAF. Hamstrings vs. patella tendon for anterior cruciate ligament reconstruction: a randomised controlled trial. *Knee*. 2001;8(1):45–50.
5. Keays SL, Bullock-Saxton JE, Keays AC, Newcombe P. Muscle strength and function before and after anterior cruciate ligament reconstruction using semitendinosus and gracilis. *Knee*. 2001;8(3):229–234.
6. Mattacola CG, Perrin DH, Gansneder BM, Gieck JH, Saliba EN, McCue FC III. Strength, functional outcome, and postural stability after anterior cruciate ligament reconstruction. *J Athl Train*. 2002;37(3):262–268.
7. Bates BT, James CR, Dufek JS. Single-subject analysis. In: Stergiou N, ed. *Innovative Analyses of Human Movement*. Champaign, IL: Human Kinetics; 2003:3–28.
8. O'Connor DP, Laughlin MS, Woods GW. Factors related to additional knee injuries after anterior cruciate ligament injury. *Arthroscopy*. 2005;21(4):431–438.
9. Irrgang JJ, Anderson AF, Boland AL, et al. Development and validation of the International Knee Documentation Committee Subjective Knee Form. *Am J Sports Med*. 2001;29(5):600–613.
10. Anderson AF, Irrgang JJ, Kocher MS, Mann BJ, Harrast JJ. International Knee Documentation Committee. The International Knee Documentation Committee Subjective Knee Evaluation Form: normative data. *Am J Sports Med*. 2006;34(1):128–135.
11. Bolgla LA, Keskula DR. Reliability of lower extremity functional performance tests. *J Orthop Sports Phys Ther*. 1997;26(3): 138–142.
12. Clark NC. Functional performance testing following knee ligament injury. *Phys Ther Sport*. 2001;2(2):91–105.
13. Harrison AJ, Keane SP, Coglan J. Force-velocity relationship and stretch-shortening cycle function in sprint and endurance athletes. *J Strength Cond Res*. 2004;18(3):473–479.
14. Arampatzis A, Schade F, Walsh M, Brüggemann GP. Influence of leg stiffness and its effect on myodynamic jumping performance. *J Electromyogr Kinesiol*. 2001;11(5):355–364.
15. McMahon TA, Cheng GC. The mechanics of running: how does stiffness couple with speed? *J Biomech*. 1990;23(suppl 1):65–78.
16. Young W. Laboratory strength assessment of athletes. *New Stud Athl*. 1995;10(1):88–96.
17. Levine TR, Hullett CR. Eta squared, partial eta squared, and misreporting of effect size in communication research. *Hum Commun Res*. 2002;28(4):612–625.
18. Cohen J. *Statistical Power Analysis for the Behavioral Sciences*. Hillsdale, NJ: Lawrence Erlbaum Assoc; 1988.
19. Barber SD, Noyes FR, Mangine RE, McCloskey JW, Hartman W. Quantitative assessment of functional limitations in normal and anterior cruciate ligament-deficient knees. *Clin Orthop Rel Res*. 1990;255:204–214.
20. Noyes FR, Barber SD, Mangine RE. Abnormal lower limb symmetry determined by function hop tests after anterior cruciate ligament rupture. *Am J Sports Med*. 1990;19(5):513–518.
21. Myklebust G, Bahr R. Return to play guidelines after anterior cruciate ligament surgery. *Br J Sports Med*. 2005;39(3):127–131.
22. Dalleau G, Belli A, Bourdin M, Lacour JR. The spring mass model and the energy cost of treadmill running. *Eur J Appl Physiol Occup Physiol*. 1998;77(3):257–263.
23. Riemann BL, Lephart SM. The sensorimotor system, part II: the role of proprioception in motor control and functional joint stability. *J Athl Train*. 2002;37(1):80–84.
24. Butler RJ, Crowell III HP, McClay Davis I. Lower extremity stiffness: implications for performance and injury. *Clin Biomech (Bristol, Avon)*. 2003;18(6):511–517.
25. Wilson GJ, Elliott BC, Wood GA. The effect on performance of imposing a delay during a stretch-shorten cycle movement. *Med Sci Sports Exerc*. 1991;23(3):364–370.
26. Chelly SM, Denis C. Leg power and hopping stiffness: relationship with sprint running performance. *Med Sci Sports Exerc*. 2001;33(2): 326–333.
27. Arampatzis A, Brüggemann GP, Metzler V. The effect of speed on leg stiffness and joint kinematics on human running. *J Biomech*. 1999;32(12):1349–1353.
28. Flanagan EP, Harrison AJ. Muscle dynamics differences between legs in healthy adults. *J Strength Cond Res*. 2007;21(1):67–72.
29. Morrow JR Jr, Jackson AW. How "significant" is your reliability? *Res Q Exerc Sport*. 1993;64(3):352–355.
30. Johansson H, Sjölander P, Sojka P. A sensory role for the cruciate ligaments. *Clin Orthop Rel Res*. 1991;268:161–178.
31. Lephart SM, Pincivero DM, Giraldo JL, Fu FH. The role of proprioception in the management and rehabilitation of athletic injuries. *Am J Sports Med*. 1997;25(1):130–137.

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