Relationship Between Isokinetic Knee Strength and Single-Leg Drop Jump Performance 9 Months After ACL Reconstruction

N.M. Nuala Crotty,* MB, BCh, BAO, Katherine A.J. Daniels,†‡ PhD, Ciaran McFadden,†§ BSc, (Hons), Niall Cafferkey,† MSc, and Enda King,†§ PT, PhD

Investigation performed at Sports Medicine Research Department, Sports Surgery Clinic, Dublin, Ireland

Background: Deficits in knee strength after anterior cruciate ligament reconstruction (ACLR) surgery are common. Deficits in the single-leg drop jump (SLDJ), a test of plyometric ability, are also found.

Purpose: To examine the relationship between isokinetic knee strength, SLDJ performance, and self-reported knee function 9 months after ACLR.

Study Design: Cross-sectional study; Level of evidence, 3.

Methods: Knee isokinetic peak torque, SLDJ jump height, contact time, and reactive strength index (RSI), as well as International Knee Documentation Committee (IKDC) scores were assessed in 116 male, field-sport athletes at 9.2 months after ACLR. SLDJ testing took place in a 3-dimensional biomechanics laboratory. Linear regression models were used to analyze the relationship between the variables.

Results: A significant relationship was found between ACLR-limb isokinetic knee extensor strength and SLDJ jump height (P < .001, r² = 0.29) and RSI (P < .001, r² = 0.33), and between ACLR-limb isokinetic knee flexor strength and SLDJ jump height (P < .001, r² = 0.12) and RSI (P < .001, r² = 0.15). A significant positive relationship was also found between knee extensor asymmetry and SLDJ jump height asymmetry (P < .001, r² = 0.27) and SLDJ reactive strength asymmetry (P < .001, r² = 0.18). Combined ACLR-limb jump height and contact time best predicted IKDC scores (P < .001, r² = 0.12).

Conclusion: Isokinetic knee extension strength explained approximately 30% of SLDJ performance, with a much weaker relationship between knee flexion strength and SLDJ performance. Isokinetic strength and SLDJ performance were weak predictors of variation in IKDC scores.

Keywords: anterior cruciate ligament reconstruction; return to sport; muscle strength; plyometric exercise; exercise test

Anterior cruciate ligament (ACL) injury is a common and disabling injury in both professional and amateur sports,2,12 and many athletes who sustain an ACL rupture undergo surgery in the hope of returning to their preinjury level of sport.1,4 However, return-to-sport (RTS) outcomes after ACL reconstruction (ACLR) are less than satisfactory, with approximately only 60% of nonelite and 83% of elite athletes returning to their preinjury level of performance.3,24 Knee extensor strength is one of the main criteria used for determining readiness to RTS,9 as marked quadriceps muscle inhibition and atrophy are frequently found after ACLR.32,41 Impairment in knee flexor strength is also common after ACLR but is less consistently seen.34

In addition to strength deficits, impairments in plyometric performance are common after ACLR.1,21,22 Plyometric movements are characterized by a stretch-shortening cycle, which involves a rapid eccentric stretch/load, followed by a brief amortization or transition phase, and then a powerful concentric muscle contraction.10 Because it is preceded by an eccentric stretch, the ensuing concentric muscle contraction is more rapid and powerful than if it occurred in isolation.10,27 Consequently, plyometric movements facilitate the force, power, and explosive ability that are needed for optimal performance of a variety of athletic tasks.13,28 The drop jump is a plyometric movement that involves dropping from a height to the ground (causing eccentric stretch/load) and minimizing ground contact time (amortization phase)
before jumping as high as possible (concentric contraction).<sup>23</sup> When incorporated into training, drop jumps have been shown to improve athletic performance.<sup>3,5,8</sup> Drop jump performance is typically quantified and assessed using jump height, ground contact time, and reactive strength index (RSI) as metrics. As the quotient of jump height and contact time, the RSI is considered a measure of reactive strength<sup>6</sup> or plyometric ability.<sup>17</sup> Compared with other measures of explosiveness, such as the single-leg hop for distance and countermovement jump, which have a slower eccentric phase, drop jumps focus on a shorter ground contact time and are therefore a better test of plyometric ability.<sup>17</sup> The single-leg drop jump (SLDJ) is less commonly used for assessment of plyometric ability after ACLR than the double-leg drop jump, even though it is less susceptible to compensation by the uninjured limb. It also more closely simulates athletic tasks that involve an eccentric preload followed by propulsion off a single leg,<sup>40</sup> such as sprinting or a change of direction. Moreover, previous research suggests that the SLDJ is more likely to expose performance deficits in the late rehabilitation phase after ACLR than more commonly used jump and change-of-direction tests,<sup>21,22</sup> and SLDJ performance has recently been shown to be a key measure in predicting the risk of contralateral limb ACL rupture.<sup>29</sup> In light of this and the importance of plyometric ability to athletic performance, the SLDJ would appear to be a clinically relevant test at this time point.

While the relationship between knee strength and hop test performance after ACLR has been investigated,<sup>31,37</sup> no study has evaluated the relationship between knee strength and SLDJ performance after ACLR. Understanding the extent of this relationship would highlight to what degree improvements in strength metrics should be expected to translate to improved SLDJ performance, and the extent to which the SLDJ needs to be specifically targeted in rehabilitation to improve plyometric performance before RTS. The primary aim of this study was therefore to assess the extent to which variation in isokinetic knee strength could explain variation in SLDJ performance measures 9 months after ACLR. In addition, while previous research<sup>1,8,37</sup> has investigated the relationship between knee strength and subjective knee function, plyometric ability has not been incorporated into these investigations. Thus, the secondary aim of this study was to assess whether SLDJ performance and knee strength would better explain the variation in self-reported knee symptoms and function as quantified by the International Knee Documentation Committee (IKDC) questionnaire than knee strength alone. We hypothesized that variation in knee extensor strength would explain a sizable portion of variation in drop jump performance, and more than variation in knee flexor strength would. We also hypothesized that the addition of SLDJ would better explain variation in IKDC scores than knee strength alone.

**METHODS**

**Participants**

Study participants were recruited from January 2014 to December 2015 from the preoperative caseloads of 2 orthopaedic surgeons whose practice consisted primarily of sport-related knee surgery. The number of athletes who fit the inclusion criteria during the study period determined the sample size. Participants were part of a longer-term research project,<sup>21</sup> and all provided written informed consent before participation. The study received ethical approval from the institution’s research ethics committee.

Inclusion criteria for the study were male, multidirectional field athletes aged 18 to 35 years who were diagnosed with an ACL rupture. Athletes with multiple ligament reconstructions, those who had revision ACL surgery, and those who stated preoperatively that they did not intend to return to multidirectional sport after surgery were excluded from the study. All participants underwent ACLR surgery with a bone—patellar tendon—bone (BPTB) or semitendinosus and gracilis hamstring tendon (HT) autograft.

**Study Design**

After surgery all participants underwent a rehabilitation protocol consisting of weightbearing as tolerated on crutches for 2 weeks, followed by progressive blocks of strength, power, and plyometric exercises, and progressing to on-field running and change-of-direction drills.<sup>22</sup> Their local physical therapist oversaw and progressed the athlete through the rehabilitation program, and an orthopaedic surgeon reviewed the progression at regular intervals. For the purposes of this study, SLDJ performance testing and strength testing of the knee flexors and extensors using isokinetic dynamometry were conducted approximately 9 months (mean ± SD, 9.2 ± 0.5 months) after surgery. All participants completed the IKDC questionnaire assessing self-reported knee symptoms and function<sup>19</sup> on the same day as the physical testing.

SLDJ testing took place in a 3-dimensional biomechanics laboratory.<sup>21,22</sup> Participants were instructed to roll from

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<sup>1</sup>Address correspondence to Enda King, PT, PhD, Sports Surgery Clinic Sports Medicine, Unit C10, Gulliver’s Retail Park, Northwood Avenue, Santry, Dublin 9, Ireland (email: endaking@hotmail.com) (Twitter: @enda_king).

<sup>2</sup>School of Medicine, Trinity College Dublin, Dublin, Ireland.

<sup>3</sup>Sports Medicine Research Department, Sports Surgery Clinic, Dublin, Ireland.

<sup>4</sup>Queen’s School of Engineering, University of Bristol, Bristol, UK.

<sup>5</sup>Department of Life Sciences, University of Roehampton, London, UK.

Final revision submitted July 21, 2021; accepted August 24, 2021. The authors declared that they have no conflicts of interest in the authorship and publication of this contribution. AOSSM checks author disclosures against the Open Payments Database (OPD). AOSSM has not conducted an independent investigation on the OPD and disclaims any liability or responsibility relating thereto.

Ethical approval for this study was obtained from Sports Surgery Clinic (ref No. 25-AFM-010).
a 20-cm step, land on 1 leg on a force platform (1000 Hz; BP400600; AMTI), and then jump as high as they could while minimizing the length of time in contact with the force platform. The force platform was synchronized with an 8-camera motion analysis system (200 Hz; Bonita-B10; Vicon) that recorded the trajectories of 24 reflective markers secured to the participant over anatomic landmarks. Motion and force data were low-pass filtered using a zero-lag, fourth-order Butterworth filter (cutoff frequency, 15 Hz). The position of the body’s center of mass (COM) was calculated from segment kinematics and inertial properties on a frame-by-frame basis as per the Vicon Plug-In Gait model (Vicon Motion Systems).29

For the jump to be valid, the participants had to keep their hands on their hips throughout the entire jump, exert maximum effort, and make full foot contact on the force platform. The participant had a rest period of 30 seconds between attempts, and the nonoperated limb was tested first. Participants performed 2 submaximal practice trials before testing. The mean of 3 valid attempts for each limb was used for further analysis. Contact time was defined as the time from the instant the ground-reaction force (GRF) first increased above 20 N to the instance of takeoff, when the GRF next dropped below 20 N. Jump height was measured as the displacement of the individual’s COM from the moment of takeoff to the moment of maximal vertical height of the COM during the aerial phase of the jump. RSI was calculated as the quotient of jump height and contact time.

Isokinetic testing took place approximately 10 to 15 minutes after jump testing and was used to determine concentric knee extensor peak torque (KE) and knee flexor peak torque (KF) for both the ACLR and the contralateral, non-ACLR limb. Based on previous recommendations,44 testing was carried out seated at an angular velocity of 60 deg/s through a knee flexion range of 0° to 100°, with a correction for gravity applied (model Cybex NORM; Computer Sports Medicine Inc). After a warm-up set, the athlete completed 2 maximal extension and flexion sets of 5 repetitions, during which they received verbal encouragement to give maximal effort, and make full foot contact on the platform. The force platform was synchronized with a 3-camera motion analysis system (Bonita-B10, Vicon). Vicon Plug-In Gait model (Vicon Motion Systems).29

The means ± standard deviations of each isokinetic (KE and KF), SLDJ performance (jump height, contact time, and RSI), and corresponding asymmetry (LSI) variable were calculated. Initially, linear regression models were used to examine the relationship between the ACLR-limb isokinetic strength and strength LSI (predictor) variables and SLDJ performance (predictive) variables. Forward, stepwise multivariable regression models with incorporated significant individual predictor variables were then developed. Standardized coefficients and adjusted $r^2$ values were reported. Subsequent analysis examined the ability of each ACLR-limb isokinetic and SLDJ performance variable as well as each LSI variable to predict IKDC scores. Variables with statistically significant individual explanatory power for IKDC were included in the initial list of variables to consider for stepwise multivariable analysis. Variables were submitted to a multiple linear regression and assessed for collinearity using variance inflation factor (VIF) values. The variable with the highest VIF value was removed from the model, and this process was repeated iteratively until all VIF values were less than 5.25 The variables remaining after this step were ACLR-limb SLDJ jump height, ACLR-limb SLDJ contact time, and ACLR-limb KE. These variables were added sequentially into the model.

**RESULTS**

A total of 116 eligible male participants (age, 24.3 ± 6.5 years; body mass, 83.8 ± 8.9 kg; height, 181 ± 6.0 cm) were recruited. The majority (n = 89) played Gaelic football, 20 played rugby, 17 played soccer, and 3 played other sports (some played more than one sport); 87 (75%) and 29 (25%) had received a BPTB or HT graft, respectively. The mean SLDJ performance and isokinetic results for both the ACLR and non-ACLR limbs are shown in Table 1. The LSIs for SLDJ jump height, RSI, and contact time were 75.7 ± 25.1%, 73.8% ± 41.4%, and 104 ± 13.7%, respectively. The LSIs for knee flexion and extension were 98.1 ± 14.5% and 83.3% ± 13.6%, respectively. The mean score on the IKDC questionnaire was 86.3 (± 10).

**TABLE 1**

| Variable         | ACLR   | Non-ACLR | LSI, % |
|------------------|--------|----------|--------|
| SLDJ JH, cm      | 9.4 ± 3.3 | 12.3 ± 2.8 | 75.7 ± 25.1 |
| SLDJ CT, s       | 0.37 ± 0.10 | 0.36 ± 0.10 | 104 ± 13.7  |
| SLDJ RSI, m/s    | 0.27 ± 0.11 | 0.36 ± 0.12 | 73.8 ± 41.4 |
| KE, N·m/kg × 100 | 227.5 ± 51.6 | 271.4 ± 37.8 | 83.3 ± 13.6  |
| KF, N·m/kg × 100 | 157.5 ± 30.7 | 161.5 ± 26.7 | 98.1 ± 14.5  |

*Data are reported as mean ± SD. ACLR, anterior cruciate ligament reconstruction; CT, contact time; JH, jump height; KE, isokinetic knee extensor peak torque; KF, isokinetic knee flexor peak torque; LSI, limb symmetry index; RSI, reactive strength index; SLDJ, single-leg drop jump.

**Statistical Analysis**

The means ± standard deviations of each isokinetic (KE and KF), SLDJ performance (jump height, contact time, and RSI), and corresponding asymmetry (LSI) variable were calculated. Initially, linear regression models were used to examine the relationship between the ACLR-limb isokinetic strength and strength LSI (predictor) variables and SLDJ performance (predictive) variables. Forward, stepwise multivariable regression models with incorporated significant individual predictor variables were then developed. Standardized coefficients and adjusted $r^2$ values were reported. Subsequent analysis examined the ability of each ACLR-limb isokinetic and SLDJ performance variable as well as each LSI variable to predict IKDC scores. Variables with statistically significant individual explanatory power for IKDC were included in the initial list of variables to consider for stepwise multivariable analysis. Variables were submitted to a multiple linear regression and assessed for collinearity using variance inflation factor (VIF) values. The variable with the highest VIF value was removed from the model, and this process was repeated iteratively until all VIF values were less than 5.25 The variables remaining after this step were ACLR-limb SLDJ jump height, ACLR-limb SLDJ contact time, and ACLR-limb KE. These variables were added sequentially into the model.

**Relationship Between Isokinetic Strength and SLDJ Performance Variables for the ACLR Limb**

The results from the linear regression analyses of ACLR-limb isokinetic and ACLR-limb SLDJ performance variables are presented in Table 2. A significant positive
relationship was found between ACLR-limb KE and SLDJ jump height \((P < .001, r^2 = 0.29)\) and RSI \((P < .001, r^2 = 0.33)\) (Figure 1, A and B). Similarly, there was a significant positive relationship between ACLR-limb KF and SLDJ jump height \((P < .001, r^2 = 0.12)\) and RSI \((P < .001, r^2 = 0.15)\) (Appendix Figure A1, B and D). A significant negative relationship was observed between ACLR-limb KE and SLDJ contact time \((P < .001, r^2 = 0.10)\), as well as between ACLR-limb KF and SLDJ contact time \((P = .003, r^2 = 0.08)\) (Appendix Figure A1, A and C).

Multivariable regression analysis found a significant positive relationship between ACLR-limb isokinetic variables (KE and KF) and both SLDJ jump height \((P < .001, r^2 = 0.28)\) and SLDJ RSI \((P < .001, \text{adjusted } r^2 = 0.32)\). A significant negative relationship was observed between ACLR-limb isokinetic variables and SLDJ contact time \((P < .001, \text{adjusted } r^2 = 0.10)\).

### Relationship Between LSIs of Isokinetic Strength and SLDJ Performance Variables

The results from the linear regression analyses of LSIs for isokinetic strength and SLDJ performance variables are presented in Table 3. Significant positive relationships were observed between the LSIs for KE and SLDJ jump height \((P < .001, r^2 = 0.27)\) and the LSIs for KE and SLDJ RSI \((P < .001, r^2 = 0.18)\) (Figure 1, C and D). A significant negative relationship was observed between the LSIs for

### Table 2

$r^2$ Values for Linear Regression of ACLR-Limb Isokinetic Strength Against ACLR-Limb SLDJ Performance Variables

| Isokinetic Variable | SLDJ JH  | SLDJ CT  | SLDJ RSI |
|---------------------|---------|---------|---------|
| KE                  | 0.29$^a$ | 0.10$^a$ | 0.33$^a$ |
| KF                  | 0.12$^a$ | 0.08$^a$ | 0.15$^a$ |
| Combined KE and KF$^b$ | 0.28$^a$ | 0.10$^a$ | 0.32$^a$ |
|                     | (0.08)  | (–0.13) | (0.08)  |

$^a$ACLR, anterior cruciate ligament reconstruction; CT, contact time; JH, jump height; KE, isokinetic knee extensor peak torque; KF, isokinetic knee flexor peak torque; LSI, limb symmetry index; RSI, reactive strength index; SLDJ, single-leg drop jump.

$^b$For the multivariable regression, adjusted $r^2$ values are shown, and the standardized coefficients for significant relationships are in parentheses.

$^a$Significant at $P < .001$.

$^b$Significant at $P < .01$.

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**Figure 1.** The relationship between knee extensor strength and (A) single-leg drop jump (SLDJ) jump height and (B) SLDJ reactive strength index (RSI), and the relationship between knee extensor strength limb symmetry index (LSI) and (C) SLDJ jump height LSI and (D) SLDJ RSI LSI. Each data point represents a participant.
**TABLE 3**

### $r^2$ Values for Linear Regression Analyses of Isokinetic Strength LSI Against SLDJ Performance Variables’ LSI

| Isokinetic Variable | SLDJ JH LSI | SLDJ CT LSI | SLDJ RSI LSI |
|---------------------|-------------|-------------|-------------|
| LSI for KE          | 0.27<sup>c</sup> | <0.01       | 0.18<sup>d</sup> |
| LSI for KF          | 0.00        | 0.04<sup>e</sup> | 0.00        |
| Combined LSIs for KE and KF<sup>b</sup> | 0.26<sup>e</sup> (0.52) | 0.03<sup>e</sup> (0.41) | 0.15<sup>e</sup> (0.03) |
| KE                  |             |             |             |
| KF                  | .217        | 0.01        |             |
| LSI for SLDJ JH     | .002        | 0.08        |             |
| LSI for SLDJ RSI    | <.001       | 0.10        |             |
| LSI for SLDJ CT     | <.001       | 0.09        |             |
| LSI for KE          | .006        | 0.06        |             |
| LSI for KF          | .200        | 0.01        |             |
| Combined SLDJ JH and SLDJ CT<sup>b</sup> | <.001       | 0.12 (0.27); (–0.21) | <.001 (0.01) |

<sup>a</sup>CT, contact time; JH, jump height; KE, isokinetic knee extensor peak torque; KF, isokinetic knee flexor peak torque; LSI, limb symmetry index; RSI, reactive strength index; SLDJ, single-leg drop jump.

<sup>b</sup>For the multivariable regression, adjusted $r^2$ values are shown, and the standardized coefficients for significant relationships are in parentheses.

<sup>c</sup>Significant at $P < .001$.

<sup>d</sup>Significant at $P < .05$.

<sup>e</sup>Adjusted $r^2$ values.

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**TABLE 4**

### $P$ Values and $r^2$ Values for Linear Regression Analyses of IKDC Scores Against Isokinetic Strength or SLDJ Performance Variables<sup>a</sup>

| Performance Measure | $P$  | $r^2$ |
|---------------------|------|-------|
| SLDJ JH             | <.001 | 0.10  |
| SLDJ RSI            | <.001 | 0.10  |
| SLDJ CT             | .007  | 0.06  |
| KE                  | .016  | 0.05  |
| KF                  | .217  | 0.01  |
| LSI for SLDJ JH     | .002  | 0.08  |
| LSI for SLDJ RSI    | <.001 | 0.10  |
| LSI for SLDJ CT     | <.001 | 0.09  |
| LSI for KE          | .006  | 0.06  |
| LSI for KF          | .200  | 0.01  |
| Combined SLDJ JH and SLDJ CT<sup>b</sup> | <.001 | 0.12 (0.27); (–0.21) | <.001 (0.01) |

<sup>a</sup>CT, contact time; IKDC, International Knee Documentation Committee; JH, jump height; KE, isokinetic knee extensor peak torque; KF, isokinetic knee flexor peak torque; LSI, limb symmetry index; RSI, reactive strength index; SLDJ, single-leg drop jump.

<sup>b</sup>For the multivariable regression, adjusted $r^2$ values are shown, and the standardized coefficients for significant relationships are in parentheses.

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**DISCUSSION**

Persistent deficits in SLDJ performance have been identified after ACLR, and the RSI during SLDJ has recently been reported as a key variable in those that go on to experience a contralateral ACL injury after RTS. Knee strength is a principal criterion for assessing readiness to return, to sport at this time point. Our results supported our first hypothesis, demonstrating that variability in isokinetic KE strength for the ACLR limb explained almost one-third of the variability in the SLDJ jump height and reactive strength. The corresponding LSI variables had a similar relationship between KE and jump height and a smaller relationship between KE and reactive strength. Linear regression analysis found a significant but weak relationship between KE and SLDJ performance measures, and the multivariable regression of combined KE and KF strength actually showed a (minimally) weaker relationship with SLDJ than the relationship of KE alone to SLDJ performance. These findings indicate that regaining KE, but not KF, strength is important to the recovery of SLDJ performance, and that additional factors beyond KE contribute considerably to SLDJ performance. Combined ACLR-limb SLDJ performance and KE strength were marginally better in predicting IKDC scores than knee strength alone, thus weakly supporting our second hypothesis.
However, both measures had little ability to predict IKDC scores, suggesting a lack of association between these metrics and self-reported knee function.

Given that concentric contraction of the knee extensors and ankle plantarflexors plays a key role in the upward propulsion of the body in the concentric phase of a drop jump, it is intuitive that concentric KE explained a sizable portion of the jump height obtained. Previous research investigating the relationship between knee strength and performance on vertical jump tests observed that concentric KE, but not KF, explained 23% to 29% of the variance in jump height.15,39,43 Although these studies all show the importance of knee extension strength for vertical jump performance, the difference in kinematic variables at the knee between the countermovement jump and the drop jump and the bilateral nature of the jumps evaluated in these studies make direct comparisons to the current study challenging. Previous examinations of the relationship between knee strength and plyometric performance in athletes after ACLR have primarily focused on horizontal hop tests. In these studies, asymmetry in KE explained 14% to 25% of asymmetry in single-leg hop for distance performance and 9.2% of asymmetry in the triple hop for distance.31,37 This is overall lower than the relationship between KE and SLDJ performance seen in the current study and may be explained by the relatively greater contribution of knee extension to performance on vertical jumps compared with horizontal jumps.30 It may also partly explain the more rapid recovery of single-leg hop for distance performance in comparison with quadriceps strength and SLDJ performance after ACLR.1,21,42

Previous work examining the predictive ability of knee extension for IKDC scores reported that knee extension torque variability, but not peak torque, predicted 14% of the variance in IKDC scores. In addition, knee extension strength asymmetry did not significantly differ with respect to IKDC scores between those with higher (>90%) compared with lower (<85%) LSI measurements.37 In the current study, similar to previous research, knee strength was observed to have poor predictive value for IKDC scores at 9 months post ACLR. SLDJ performance had weak predictive ability, and the combination of knee strength and SLDJ performance did little to improve the predictive value of IKDC scores over KE alone. This suggests that other factors, such as meniscal/chondral damage at the time of initial injury,25 psychological factors,26,36 or more demanding tests, such as change of direction, may better explain IKDC scores at this time point after surgery.

It is noteworthy that, in the current study, recovery of limb symmetry in SLDJ performance (LSIs, 73.8% ± 41.4% and 75.7% ± 25.1% for RSI and JH, respectively) was considerably less than recovery in KE strength symmetry (LSI, 83.3% ± 13.6%), indicating that recovery in plyometric ability after ACLR may lag behind that of maximal strength. This finding underscores the importance of recovering strength qualities beyond maximal strength to return athletes to high performance after injury.6,8,25 Assessment and rehabilitation of these strength qualities, including reactive strength, are recommended in the later stage of ACLR rehabilitation, once sufficient maximum strength has been achieved.8 In previous research examining the SLDJ after ACLR, the SLDJ jump height demonstrated ongoing asymmetry (LSI, 79%) at 9 months, despite the single-leg hop for distance returning to normal levels (LSI, 94%).21 In another study investigating biomechanical and performance variables across a battery of jump and change-of-direction tests in athletes 9 months after ACLR compared with healthy controls, SLDJ jump height was found to have the greatest asymmetry of all measured variables. These results and those of the current study all suggest that the SLDJ is a clinically relevant test in the later stage of rehabilitation after ACLR. Furthermore, drop jumps have resulted in improvements in sprinting, jumping, and change-of-direction ability, as well as running economy, when included in a training program, indicating that recovery of drop jump performance after ACLR is important for optimization of athletic performance.

**Limitations**

This study evaluated performance variables in a specific cohort of male, multidirectional field-sport athletes, so the findings may not be generalizable to female or younger athletes. We examined the relationship between concentric peak extensor/flexor torques and plyometric performance but did not investigate other strength qualities that may also influence plyometric performance, such as rate of force development and eccentric strength.14 Finally, the study cohort consisted of athletes who had received either a BPTB or HT autograft. Graft type has been found to be associated with knee strength and jump loading asymmetry metrics after ACLR,8,30,45 so delimitation to a single graft type or the inclusion of alternative grafts may have altered our findings. Future research may explore other factors influencing SLDJ performance and interventions that may effectively address SLDJ performance deficits to optimize functional recovery after ACLR.

**CONCLUSION**

This study demonstrated that ACLR-limb KE strength could explain approximately 30% of SLDJ performance in male athletes 9 months after ACLR, with a much weaker relationship between KF and SLDJ performance. SLDJ performance variables and knee strength had little ability to explain variation in IKDC scores. These findings suggest that knee extensor strength should be targeted in post-ACLR rehabilitation to improve SLDJ performance, but that additional exercises to improve plyometric ability may be needed to optimally restore athletic performance before RTS.

**REFERENCES**

1. Abrams GD, Harris JD, Gupta AK, et al. Functional performance testing after anterior cruciate ligament reconstruction: a systematic review. *Ortho J Sports Med*. 2014;2(1):2-10.
2. Alentorn-Geli E, Myer GD, Silvers HJ, et al. Prevention of non-contact anterior cruciate ligament injuries in soccer players. Part 1:
Mechanisms of injury and underlying risk factors. *Knee Surg Sports Traumatol Arthrosoc*. 2009;17(7):705-729.

3. Ardern CL, Taylor NF, Feller JA, Webster KE. Fifty-five per cent return to competitive sport following anterior cruciate ligament reconstruction surgery: an updated systematic review and meta-analysis including aspects of physical functioning and contextual factors. *Br J Sports Med*. 2014;48(21):1543-1552.

4. Ardern CL, Webster KE, Taylor NF, Feller JA. Return to sport following anterior cruciate ligament reconstruction surgery: a systematic review and meta-analysis of the state of play. *Br J Sports Med*. 2011;45(7):596-606.

5. Bobbert MF. Drop jumping as a training method for jumping ability. *Sports Med*. 1990;9(1):7-22.

6. Beattie K, Carson BP, Lyons M, Kenny IC. The relationship between maximal strength and reactive strength. *Int J Sports Physiol Perform*. 2017;12(4):548-553.

7. Bobbert MF. Drop jumping as a training method for jumping ability. *Sports Med*. 1990;9(1):7-22.

8. Buckthorpe M. Optimising the late-stage rehabilitation and return-to-sport training and testing process after ACL reconstruction. *Sports Med*. 2019;49(7):1043-1058.

9. Burgi CR, Peters S, Ardern CL, et al. Which criteria are used to clear patients to return to sport after primary ACL reconstruction? A scoping review. *Br J Sports Med*. 2019;53(18):1154-1161.

10. Chmieliewski TL, Myer GD, Kaufman D, Tillman SM. Plyometric exercise in the rehabilitation of athletes: physiological responses and clinical application. *J Orthop Sports Phys Ther*. 2006;36(5):308-319.

11. Cox CL, Huston LJ, Dunn WR, et al. Are articular cartilage lesions and meniscus tears predictive of IKDC, KOOS, and Marx activity level outcomes after anterior cruciate ligament reconstruction? A 6-year multicenter cohort study. *Am J Sports Med*. 2014;42(5):1058-1067.

12. Czuppon S, Racette BA, Klein SE, Harris-Hayes M. Variables associated with return to sport following anterior cruciate ligament reconstruction: a systematic review. *Br J Sports Med*. 2014;48(5):356-364.

13. Davies G, Riemann BL, Manske R. Current concepts of plyometric exercise. *Int J Sports Phys Ther*. 2015;10(6):780-786.

14. Davies WT, Myer GD, Read PJ. Is it time we better understood the tests we are using for return to sport decision making following ACL reconstruction? A critical review of the hop tests. *Sports Tests*. 2020;50(3):485-495.

15. De Staso J, Kaminski TW, Perrim DH. Relationship between drop jump vertical heights and isokinetic measures utilising the stretch-shortening cycle. *Isokinets Exerc Sci*. 1997;6:175-179.

16. Feller JA, Webster KE. A randomized comparison of patellar tendon and hamstring tendon anterior cruciate ligament reconstruction. *Am J Sports Med*. 2003;31(4):564-573.

17. Flanagan EP, Comyns TM. The use of contact time and the reactive stretch index to optimize the fast stretch-shortening cycle in training. *Strength Cond J*. 2008;30(3):32-38.

18. Goetschius J, Hart JM. Knee-extension torque variability and subjective knee function in patients with a history of anterior cruciate ligament reconstruction. *J Athl Train*. 2016;51(1):22-27.

19. Gravle GR, 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.

20. King E, Richter C, Daniels KAJ, et al. Biomechanical testing after anterior cruciate ligament reconstruction: a systematic review with meta-analysis of return to sport rates, graft rupture rates and performance outcomes. *Br J Sports Med*. 2018;52(2):128-138.

21. Lai CCH, Ardern CL, Feller JA, Webster KE. Eighty-three per cent of elite athletes return to preinjury sport after anterior cruciate ligament reconstruction: a systematic review with meta-analysis of return to sport rates, graft rupture rates and performance outcomes. *Br J Sports Med*. 2018;52(2):128-138.

22. Lenz TA, Zeppler G Jr, George SZ, et al. Comparison of physical impairment, functional, and psychosocial measures based on fear of reinjury/lack of confidence and return-to-sport status after ACL reconstruction. *Am J Sports Med*. 2015;43(2):345-353.

23. Koch N, Lynn GS. Linear collinearity and misleading results in variance-based SEM: an illustration and recommendations. *J Assoc Inf Syst*. 2012;13(7):546-580.

24. Lai CCH, Ardern CL, Feller JA, Webster KE. Eighty-three per cent of elite athletes return to preinjury sport after anterior cruciate ligament reconstruction: a systematic review with meta-analysis of return to sport rates, graft rupture rates and performance outcomes. *Br J Sports Med*. 2018;52(2):128-138.

25. Malteson L, Read P, Bishop C, Turner A. Strength and power training in rehabilitation: underpinning principles and practical strategies to return athletes to high performance. *Sports Med*. 2020;50(2):239-252.

26. Malisoux L, Francaux M, Nielsens H, Theisen D. Stretch-shortening cycle exercises: an effective training paradigm to enhance power output of human single muscle fibers. *J Appl Physiol*. 2006;100:771-779.

27. Markovic G, Mikulic P. Neuro-musculoskeletal and performance adaptations to lower-extremity plyometric training. *Sports Med*. 2010;40(10):859-895.

28. Marshall BM, Franklyn-Miller AD, King EA, et al. Biomechanical factors associated with time to complete a change of direction cutting maneuver. *J Strength Cond Res*. 2014;28(10):2845-2851.

29. Miles JJ, King E, Falvey EC, Daniels KAJ. Patellar and hamstring auto-graphics are associated with different jump task loading asymmetries after ACL reconstruction. *Scand J Med Sci Sports*. 2019;29(8):1212-1222.

30. Palmieri-Smith RM, Lepley LK. Quadriceps strength asymmetry after anterior cruciate ligament reconstruction alters knee joint biomechanics and functional performance at time of return to activity. *Am J Sports Med*. 2015;43(7):1662-1669.

31. Palmieri-Smith RM, Thomas AC, Woljys EM. Maximizing quadriceps strength after ACL reconstruction. *Clin Sports Med*. 2008;27(3):405-424, vii ix.

32. Pedley JS, Lloyd RS, Read P, Moore I, Oliver JL. Drop jump: a technical model for scientific application. *Strength Cond J*. 2017;39(5):36-44.

33. Petersen W, Taheri P, Forkel P, Zontop T. Return to play following ACL reconstruction: a systematic review about strength deficits. *Arch Orthop Trauma Surg*. 2014;134(10):1417-1428.

34. Robertson DG, Fleming D. Kinetics of standing broad and vertical jumps. *Can J Sports Sci*. 1987;12(1):19-23.

35. Rosso F, Bonasia DE, Cottino U, et al. Factors affecting subjective and objective outcomes and return to play in anterior cruciate liga- ment reconstruction: a retrospective cohort study. *Joints*. 2018;6(1): 23-32.

36. Schmitt LC, Paterno MV, Hewett TE. The impact of quadriceps femoris strength asymmetry on functional performance at return to sport following anterior cruciate ligament reconstruction. *J Orthop Phys Sports Phys*. 2012;42(9):750-759.

37. Simlan M, Chamami K, Milka B, Del Vecchio FB, Chéour F. Effects of plyometric training on physical fitness in team sport athletes: a sys- tematic review. *J Hum Kinet*. 2016;52:231-247.

38. Śliwowski R, Grygorowicz M, Wieszcak A, Jadczak L. The relationship between jumping performance, isokinetic strength and dynamic postural control in elite youth soccer players. *J Sports Med Phys Fitness*. 2018;58(9):1226-1233.

39. Stalbom M, Holm DJ, Cronin J, Keogh J. Reliability of kinematics and kinetics associated with horizontal single leg drop jump assessment. A brief report. *J Sports Sci Med*. 2007;6(2):261-264.

40. Thomas AC, Woljys EM, Brandon C, Palmieri-Smith RM. Muscle atro- phy contributes to quadriceps weakness after anterior cruciate liga- ment reconstruction. *Am J Sports Med*. 2016;44(1):7-11.

41. Thomée R, Neeter C, Gustavsson A, et al. Variability in leg muscle force and hop performance after anterior cruciate ligament reconstruc- tion. *Knee Surg Sports Traumatol Arthrosoc*. 2012;20(6):1143-1151.

42. Tsikanos A, Kellis E, Jamurtas A, Kellis S. The relationship between jumping performance and isokinetic strength of hip and knee exten- sors and ankle plantar flexors. *Isokinets Exerc Sci*. 2002;10:107-115.
44. Undheim MB, Cosgrave C, King E, et al. Isokinetic muscle strength and readiness to return to sport following anterior cruciate ligament reconstruction: is there an association? A systematic review and a protocol recommendation. Br J Sports Med. 2015;49(20):1305-1310.

45. Xergia SA, McClelland JA, Kvist J, Vasiladis HS, Georgoulis AD. The influence of graft choice on isokinetic muscle strength 4-24 months after anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc. 2011;19(5):768-780.

APPENDIX

Figure A1. The relationship between (A) knee extensor strength and single-leg drop jump (SLD) contact time, and the relationship between knee flexor strength and (B) SLDJ jump height, (C) SLDJ contact time, and (D) SLDJ reactive strength index (RSI). Each data point represents a participant.

Figure A2. The relationship between knee flexor strength limb symmetry index (LSI) and single-leg drop jump (SLDJ) contact time LSI. Each data point represents a participant.
Figure A3. The relationship between (A) single-leg drop jump (SLDJ) jump height, (B) SLDJ reactive strength index (RSI), (C) SLDJ contact time, and (D) knee extensor strength and International Knee Documentation Committee (IKDC) score. Each data point represents a participant.

Figure A4. The relationship between (A) single-leg drop jump (SLDJ) jump height limb symmetry index (LSI), (B) SLDJ reactive strength index (RSI) LSI, (C) SLDJ contact time LSI, and (D) knee extensor strength LSI and International Knee Documentation Committee (IKDC) score. Each data point represents a participant.