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Residual Deficits in Reactive Strength After Anterior Cruciate Ligament Reconstruction in Soccer Players

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Context: Deficits in plyometric abilities are common after anterior cruciate ligament reconstruction (ACLR). Vertical rebound tasks may provide a targeted evaluation of knee function.

Objective: To examine the utility of a vertical hop test for assessing function after ACLR and establishing factors associated with performance.

Design: Cross-sectional study.

Setting: Rehabilitation program.

Patients or Other Participants: Soccer players with a history of ACLR (n = 73) and matched control individuals (n = 195).

Main Outcome Measure(s): The 10-second vertical hop test provided measures of jump height, the Reactive Strength Index (RSI), and asymmetry. We also examined possible predictors of hop performance, including single-legged vertical drop jump, isokinetic knee-extension strength, and the International Knee Documentation Committee questionnaire score.

Results: Between-limbs differences were identified only for the ACLR group, and asymmetry scores increased in those with a history of ACLR ($P < .001$) compared with the control group. The single-legged vertical drop jump, RSI, and knee-extension torque were significant predictors of 10-second hop height ($R^2 = 20.1\%$) and RSI ($R^2 = 47.1\%$).

Conclusions: Vertical hop deficits were present after ACLR, even after participants completed a comprehensive rehabilitation program. This may have been due to reduced knee-extension and reactive strength. Vertical hop tests warrant inclusion as part of the return-to-sport test battery.

Key Words: Reactive Strength Index, plyometrics, movement assessment, return to sport

Key Points

- Compared with a matched control group, soccer players in the later stages of rehabilitation after anterior cruciate ligament reconstruction (ACLR) displayed lower-level performances and greater asymmetry in 10-second hop outcome measures.
- Worse 10-second hop performance after ACLR may be attributed in part to residual deficits in knee-extension and reactive strength.
- After ACLR, participants' asymmetry scores during the 10-second hop test were greater (by ~25%) than previous values suggested for acceptable discharge from rehabilitation in traditional horizontal hop tests (eg, >90% Limb Symmetry Index). Thus, vertical rebound tasks may be more sensitive in identifying deficits in knee function.

Residual deficits after anterior cruciate ligament reconstruction (ACLR) suggest incomplete rehabilitation of the injured limb.[1,2] Vertical jump tests are a valid measure of functional performance and demonstrate only moderate associations with commonly used horizontal hop protocols.[3] Vertical jumping requires greater contributions from the knee to perform the external work,[4] providing a more targeted evaluation of dynamic knee function. Researchers[5] have observed a delay in achieving recommended Limb Symmetry Index (LSI) values (>90%) during vertical jumps compared with horizontal hopping after ACLR. Recent investigators[6] also showed that single-legged drop vertical jumps revealed greater deficits at 9 months after ACLR than the single-legged hop for distance in team-sport athletes. However, these findings were inconsistent.[7,8]

Measurements of horizontal hop distance and vertical jump height are common when assessing readiness to return to sport (RTS).[9] Yet these variables do not account for alterations in jump strategy,[10] lack sensitivity to identify deficits in knee function,[11] and display weak associations with known injury mechanisms, including change of direction.[12] When assessing athletes after ACLR, it is important to consider compensatory strategies. When performing a rebound test on the involved limb, individuals can increase their ground contact time to produce the force needed for propulsion and compensate for reduced stretch-shortening cycle (SSC) function. This athletic ability can be quantified using the Reactive Strength Index (RSI).[13] Longer amortization suggests an inability to attenuate ground reaction forces on landing[14] and is associated with reduced knee-extension force output during the concentric phase of a vertical jump.[15]

The 10-second single-legged hop (10-second hop) has been used sparingly to assess functional performance after ACLR.[2,16] This test can account for the limitations inherent in measuring jump height or hop distance alone. Petschnig et al[16] reported a greater ability to identify performance deficits in individuals with ACLR who were 54 weeks postsurgery during the 10-second hop test than with both the single and triple hop for distance. Specifically, LSI scores were below specified thresholds (<85%) only for this functional test. Similarly, Myer et al[2] showed differences in jump height LSI and normalized vertical ground reaction force at the time of RTS compared with matched control participants. However, neither study included elite athletes, and Myer et al[2] used a force plate. Practically viable assessment modes and normative values in elite athletes are required to help guide practitioners and inform RTS decision making.

An individual's subjective perception of knee function is also commonly evaluated after ACLR.[17–20] Previous researchers[17–20] found moderate correlations between self-reported function and hop performance approximately 6 months postsurgery. Limited data are available to examine relationships between subjective ratings of knee function and performance during vertical rebound tasks. More symmetric quadriceps strength has been cited as an important determinant of safe and effective RTS[21] and is associated with greater symmetry during a bilateral drop jump task,[22] but the contribution of quadriceps strength to unilateral rebound tasks is unknown. In addition, the RSI is underpinned by SSC function, which is used in many sporting movements, such as running and change of direction. The most common mode of assessment for assessing this physical characteristic has been drop jump protocols using a force platform.[13] Understanding constructs of performance during dynamic tests of knee function using practically viable tests and considering both objective and subjective measures can help practitioners design targeted reconditioning programs.

In this study, we had 2 aims: (1) assess functional performance using a practically viable 10-second hop test in soccer players who were either currently playing and free from injury or at the end stages of their rehabilitation after ACLR and (2) examine relationships and predictive factors associated with 10-second hop height and the RSI to determine the tests' performance constructs. We hypothesized that deficits in 10-second hop performance would be evident in those with a history of ACLR, and performance on this test would be explained, at least in part, by knee-extension and reactive strength.

METHODS

Experimental Approach to the Problem

Individuals who had undergone ACLR and control individuals attended a formal testing session during which they performed the 10-second hop test. Surrogate predictors of 10-second hop height and the RSI were also evaluated in ACLR participants only to determine factors associated with successful performance. These included the single-legged drop vertical jump (SLDVJ) RSI, isokinetic knee-extension strength, and patient-reported function via the International Knee Documentation Committee (IKDC) questionnaire. All data were collected in a single appointment for athletes with ACLR who had obtained physiotherapy clearance before performing all tests and for control individuals as part of a periodic health screening. The prescribed test order was as follows: IKDC, SLDVJ, 10-second hop, and isokinetic assessment.

Participants

We recruited 268 male soccer players who volunteered to take part in this study. Participants were divided: group 1 (players who were $\geq$6 months post-ACLR; age = 24.2 $\pm$ 5.1 years, height = 174.9 $\pm$ 7.6 cm, mass = 70.9 $\pm$ 10.2 kg) and group 2 (uninjured matched control participants; age = 24.7 $\pm$ 4.3 years, height = 175.3 $\pm$ 6.9 cm, mass = 71.4 $\pm$ 9.1 kg). The ACLR and control groups consisted of soccer players from teams who competed in 1 of the recognized leagues as part of the Qatar Football Association. Athletes in the matched control group attended Aspetar Orthopaedic and Sports Medicine Hospital while taking part in an annual periodic health evaluation.

The inclusion criteria for the ACLR group required athletes to be male, have undergone primary surgical reconstruction, and have competed as a registered soccer player in 1 of the recognized competitive leagues of the Qatar Football Association before their injury. Players were excluded if they reported a history of previous ACL injury or surgery that was not associated with the primary surgical reconstruction, other knee ligament or cartilage injury, or previous surgery on either the ACLR or contralateral leg. Matched control individuals were at the same competitive standard, had no history of ACL or other serious knee injury, and were free from *severe injury* (defined as >28 days' time loss) in the previous 12 months, verified by inspection of a national injury audit. Informed written consent and ethical approval were obtained before testing. This study was approved by the Anti-Doping Laboratory, Doha, Qatar (IRB: F2017000227).

Procedures

All players were familiarized before testing and completed a standardized warmup consisting of 5 minutes of pulse-raising activity and dynamic body weight movements. Only 1 practice trial of the 10-second hop test was performed due to the high intensity and repeated nature of the test protocol. One recorded trial of the 10-second hop test was then completed on each limb interspersed with a 60-second rest period. Limb order was randomized. All tests were conducted by an experienced strength and conditioning coach with substantial experience in the test procedures.

The 10-Second Single-Legged Hop. Repeated single-legged jumps were performed for 10 seconds in accordance with previous recommendations.[2] The test began with participants placing their hands on their hips and completing a rapid countermovement into a quarter-squat, followed by a maximal vertical jump. This action was replicated across the test period. The instructions were to jump as high as possible and minimize ground contact time while landing under control, maintaining the same footprint, and facing forward during the entire test. Bending the leg while airborne was not permitted. We used an optical measurement device consisting of a transmitting and receiving bar (model Optojump; Microgate) to quantify average jump height and the RSI derived from jump height (m) divided by ground contact time (seconds). Light-emitting diodes on the transmitting bar communicate continuously with those on the receiving bar, and the system detects any disruptions in communication between the bars, recording their duration. This allows measurement of flight and contact time. The first jump was discarded from the analysis, as this did not involve fast SSC rebound ground contact.

Single-Legged Drop Vertical Jump. The SLDVJ was performed on a force plate (version 1.2.6109 ForceDecks; Vald Performance) recording at a sampling rate of 1000 Hz. Athletes began in a unilateral stance and dropped off a 15-cm box on their designated test leg. On landing, their instructions were to minimize ground contact time and jump as high as possible. Hands were fixed on the hips throughout the test, and bending of the leg while airborne was not permitted. We quantified the RSI using the equation: jump height/ground contact time. *Ground contact time* was defined as the time at which the vertical ground reaction force exceeded 20 N to the instant of takeoff. Jump height was calculated using the athlete's center-of-mass velocity via the following equation: (center-of-mass velocity)^2/(9.81 $\times$ 2). The velocity-time record was obtained by dividing the resultant force-time record by the individual's body mass (BM) to provide acceleration and then numerically integrating with respect to time using the trapezoid rule. Three jumps were performed, with the average of all trials reported. We selected this test as the criterion standard measure to determine an individual's RSI due to its high frequency of use in the literature and the development of the RSI as originally derived from drop vertical jump protocols.[13] The drop jump is reliable,[23] and the task requires that athletes decelerate their downward motion in a yielding, or eccentric, action until reaching a point of momentary zero velocity and then immediately reverse this motion in a propulsive, or concentric, action. This assessment provides an effective means of determining SSC function.[13]

Isokinetic Knee Extension. Maximal knee-extension strength was measured using an isokinetic dynamometer (Biodex Medical Systems). Players were in a seated position with the hip flexed to 90°; all procedures replicated those of earlier researchers.[24] Assessment modes were 5 repetitions of concentric knee extension at 60°/s and 10 repetitions at 300°/s with the highest peak torque value recorded across the trials used for analysis and reported as a percentage of the individual's BM. A 60-second rest period was provided between the different testing speeds. Before each test, participants were instructed on the procedures and allowed appropriate practice repetitions. Vigorous oral encouragement was supplied throughout by the same assessor who conducted all tests.

The IKDC 2000 Questionnaire. The IKDC requires individuals to rate their current level of symptoms, ability to perform specified activities, and level of function. The full version of the questionnaire was completed independently by each ACLR group participant and scored in accordance with previous guidelines.[25] Players were familiar with the questionnaire and had completed it several times during the earlier stages of their rehabilitation. The IKDC questionnaire has been validated, shows high test-retest reliability, and is sensitive in identifying lower levels of function.[26]

Statistical Analysis

We checked the distribution of the data using the Shapiro-Wilk normality test. Descriptive statistics (mean $\pm$ SD) for all variables were calculated. Between-limbs asymmetries in the 10-second hop were quantified as the percentage difference between limbs using the following formula: (100/(maximum value) $\times$ (minimum value) $\times -1$ $+$ 100).[27] The maximum and minimum values indicate the highest and lowest performing limb, respectively, based on the average of all repetitions during the 10-second test period. We did not use the LSI, which denotes the dominant and operated legs in healthy participants and those with ACL deficiency, respectively; the equation cannot be standardized when comparing patients with ACLR and healthy matched control participants.

An independent-samples *t* test was conducted to examine differences in anthropometrics between groups, and a paired-samples *t* test was applied to measure between-limbs differences for all test variables. Cohen *d* effect sizes (ESs) were calculated to interpret the magnitude of these differences using the following classifications: standardized mean differences of 0.2, 0.5, and 0.8 for *small*, *medium*, and *large* ESs, respectively. Performance variables (jump height and RSI) and respective asymmetry thresholds were also computed across players in each group by ordering all recorded values and dividing the data for each variable into equal quartiles according to position with 4 cut points (Q1–Q4).

To determine the constructs measured via 10-second hop performance, we calculated Pearson product correlation coefficients to examine the strength of the relationships between involved-limb average 10-second hop height and RSI and the measured surrogate predictor variables of SLDVJ RSI and isokinetic peak torque measured at 60° and 300°/s (absolute and percentage of BM). Relationships with the IKDC patient-reported outcomes were assessed using Spearman correlations. The magnitude of these relationships was classified as *almost perfect* ($r = >0.9$), *very large* ($r = 0.7$–0.9), *large* ($r = 0.5$–0.7), *moderate* ($r = 0.3$–0.5), *small* ($r = 0.1$–0.3), or *trivial* ($r = <0.1$). Variables that were significantly correlated with either of the dependent variables (10-second hop height and the RSI) were entered into separate multivariate backward stepwise linear regression models. Multicollinearity was determined by assessing the variation inflation factor to ensure that values were $<$2.0 to eliminate the suggestion of strong multicollinearity with predictor variables included in the model. All data were computed via Excel (version 2010; Microsoft Corp). Also, the *t* tests, quartiles, Pearson and Spearman correlations, and multivariate linear regressions were processed using SPSS (version 22; IBM Corp). The α level of statistical significance was set at $P \leq .05$.

RESULTS

No differences in anthropometrics were noted between groups ($P > .05$). Descriptive statistics for all variables collected during the 10-second hop for the ACLR and healthy control groups are shown in Table 1. Participant groupings by quartiles for 10-second hop performance and asymmetry scores are given in Table 2. Differences were present between the involved and uninvolved limbs of the individuals with ACLR ($P < .001$; EsS = 0.29–1.16) but not the dominant and nondominant limbs of the matched control group for all variables. Between-limbs asymmetries ranged from 24.1% to 27.9% and 10.5% to 13.1% for the ACLR and matched control groups, respectively. Significant reductions in the asymmetry percentage were observed in the ACLR group for jump height and RSI.

Table 1. Descriptive Statistics for the 10-Second Hop (Mean ± SD)

Variable	Anterior Cruciate Ligament Reconstruction Group			Healthy Control Group		
	Involved Limb		Uninvolved Limb	Dominant Limb		Nondominant Limb
Jump height, cm	10.0 ± 2.7		13.2 ± 2.8[a]	13.0 ± 3.0		13.2 ± 2.9
Asymmetry, %		24.1 ± 13.7			10.5 ± 7.8[b]	
Reactive Strength Index	0.28 ± 0.08		0.39 ± 0.11[a]	0.41 ± 0.11		0.42 ± 0.10
Asymmetry, %		27.9 ± 14.5			13.1 ± 9.9[b]	

[a] Difference between the involved and uninvolved limbs ($P < .001$).
[b] Difference between anterior cruciate ligament reconstruction and healthy control groups ($P < .001$).

Descriptive statistics for SLDVJ RSI and isokinetic quadriceps peak torque in the ACLR group are shown in Table 3. Between-limbs differences were seen for all test variables (P values $< .001$). The involved-limb SLDVJ RSI ($r = 0.36$), quadriceps knee-extension torque at 60°/s (% BM; $r = 0.37$), and quadriceps knee-extension torque at 300°/s (% BM; $r = 0.33$) indicated significant moderate correlations with 10-second hop height. Similarly, these variables were significantly correlated with the RSI measured during the 10-second hop, although the strength of these relationships was classified as large for SLDVJ RSI ($r = 0.60$) and quadriceps knee-extension torque at 60°/s (% BM; $r = 0.54$). Only a moderate relationship was observed for the 10-second hop RSI and quadriceps knee-extension torque at 300°/s (% BM; $r = 0.37$). The total IKDC score was 77 ± 8 and not significantly correlated with 10-second hop performance.

Prediction models for 10-second hop height and RSI are displayed in Table 4. Using 10-second hop height as the dependent variable, a model including SLDVJ RSI and quadriceps knee-extension torque at 300°/s (% BM) indicated these variables were significant predictors ($P < .05$) explaining 20.1% of the variance in performance. The prediction accuracy of the model improved when the 10-second hop RSI was used as the dependent variable, with the SLDVJ RSI and quadriceps knee-extension torque at 300°/s (% BM) explaining 47.1% of the variance in performance.

DISCUSSION

Our primary aim was to compare the performance of soccer players who had undergone ACLR and were in the final stages of their rehabilitation with those of matched control participants in a 10-second vertical rebound task as an indicator of dynamic knee function. Differences were identified between the involved and uninvolved limbs. The jump height and RSI asymmetry scores were increased in those with a history of ACLR compared with matched control individuals. Our secondary aim was to examine relationships and predictive factors associated with the 10-second hop height and RSI to determine the test performance constructs. The SLDVJ RSI and high-velocity knee-extension torque were significant predictors of jump height and RSI, explaining approximately one-quarter and one-half of the test outcome variances, respectively, indicating that these physical qualities were contributing factors to the vertical rebound tasks emphasizing rapid SSC function.

We found differences in the 10-second hop height and RSI between the involved and uninvolved limbs of the ACLR group, with asymmetry scores greater than in the matched control group, even though the former individuals were in the later stages of a comprehensive, evidence-based rehabilitation program.[28] Performance on the SLDVJ by male multidirectional field sport athletes 9 months after reconstruction recently showed deficits for the involved leg[6]; values were comparable with those seen in the current study. Previously, a 10-second vertical jumping protocol identified between-limbs differences and comparable LSI values (74.9%) for jump height in patients 54 weeks post-ACLR.[16] Myer et al[2] also used the single-legged 10-second hop test in a cohort of male and female youth athletes who had returned to sport (9.7 months after reconstruction). They reported LSI differences for the ACLR cohort versus the control cohort (89% and 101%, respectively).

Our findings confirmed that residual deficits in force attenuation and reuse capacities were present after ACLR, as evidenced by the lower 10-second hop height and RSI. Between-limbs differences in the SLDVJ RSI with pronounced asymmetries (LSI ≅ 84%) further supported this notion. In addition, increased RSI asymmetry in a drop jump has been associated with reductions in change-of-direction performance.[27] Importantly, change of direction has been recognized as a mechanism of noncontact ACL injury.[29] Our findings suggest that targeted interventions are necessary to restore reactive strength. An effective method

Table 2. Asymmetry Thresholds for Injured and Uninjured Players in Each Quartile

Variable	Group	Quartile 1	2	3	4
Jump height, cm	ACLR	<8.2	8.3–9.6	9.7–12.3	>12.4
	Control	<11.2	11.3–13.1	13.2–15.1	>15.2
Asymmetry, %	ACLR	>33.8	33.7–24.1	24.0–14.1	<14
	Control	>16.5	16.4–9.9	9.8–4.6	<4.5
Reactive Strength Index	ACLR	<0.20	0.21–0.27	0.28–0.35	>0.36
	Control	<0.35	0.36–0.40	0.41–0.50	>0.51
Asymmetry, %	ACLR	>39.2	39.1–27.6	27.5–17.3	<17.2
	Control	>18.1	18.0–11.1	11.0–5.3	<5.2

Abbreviation: ACLR, anterior cruciate ligament reconstruction.

Table 3. Descriptive Statistics for Single-Legged Drop Vertical Jump and Isokinetic Quadriceps Peak Torque (Mean ± SD)

Test Variable	Involved Limb	Uninvolved Limb
Single-legged drop vertical jump		
Reactive Strength Index, m/s	0.79 ± 0.20	0.95 ± 0.21
LSI, %	83.7 ± 14.1	
Isokinetic peak torque, % BM		
60°/s	286 ± 47	334 ± 48
LSI, %	86.5 ± 13.4	
300°/s	164 ± 28	191 ± 35
LSI, %	87.1 ± 14.3	

Abbreviations: BM, body mass; LSI, Limb Symmetry Index.

Table 4. Linear Regression to Determine Associations With 10-Second Hop Performance

Jump Variable	Standardized β Coefficient	*P* Value	Adjusted R^2 Value
10-second hop height			
SLDVJ RSI	0.358	.007	0.201
Knee-extension torque at 300°/s, % BM	0.321	.015	
10-second hop RSI			
SLDVJ RSI	0.593	.000	0.471
Knee-extension torque at 300°/s, % BM	0.369	.001	

Abbreviations: BM, body mass; RSI, Reactive Strength Index; SLDVJ, single-legged drop vertical jump.

for increasing this physical quality is plyometric training.[14,30] Evidence indicated that plyometric training was used sparingly during ACL rehabilitation.[31] We encourage practitioners to include this training modality when appropriate and propose assessment of the RSI using a practically viable tool such as the 10-second hop to measure lower limb SSC function. Furthermore, mobile phone applications such as My Jump 2 (Carlos Balsalobre-Fernandez) can also be used, as this method provides a valid and reliable tool for measuring the RSI in vertical jump tasks.[32]

Our results indicated that the RSI measured during an SLDVJ and both low- and high-velocity knee-extension strength were most strongly associated with key performance indicators during the 10-second hop. Previous researchers have observed significant relationships between knee-extensor strength and vertical jump performance,[33] and low-velocity isokinetic quadriceps peak torque was moderately associated ($r = 0.51$) with 10-second hop performance in recreationally trained patients after ACLR.[16] The rate of torque development of the knee extensors was also associated with vertical jump performance.[34] Similarly, the knee-extension rate of torque development, in addition to the RSI measured during an SLDVJ, explained 60.9% of the variance in triple hop-for-distance scores in patients after ACLR.[15] Earlier investigators have reported deficient low-velocity knee-extension strength after ACLR,[35] and these residual deficits have been associated with an increased risk of future ACL injury.[21] The participants in our study also displayed greater between-limbs deficits in quadriceps strength (mean LSI = 86%; Table 1) than the value previously suggested (LSI > 90%) for safe RTS.[21] Cumulatively, these outcomes benefit patient decision making and suggest that both high- and low-velocity strength training should be included as part of a well-structured rehabilitation program to increase lower limb SSC function and enhance an individual's readiness to perform. Further research is warranted to examine if a lower RSI and asymmetry in this physical quality is associated with an increased risk of secondary injury after RTS post-ACLR.

Intuitively, the RSI measured during an SLDVJ and the 10-second hop would be expected to show some level of correspondence as both are unilateral rebound tasks. A large correlation was noted ($r = 0.61$) between the tests, but a substantial amount of the variance remained unexplained. The SLDVJ is a single rebound task, and drop height is constrained by asking participants to drop from a 15-cm box. The 10-second hop sets the landing height according to the individual's level of performance (ie, matched to the jump height). In addition, the longer duration and more reactive and repeated nature of the 10-second hop test may, in part, explain why the prediction accuracy of the regression model increased when the RSI was the dependent variable. The RSI is used to profile stretch load tolerance.[14] Various strategies can be employed to maintain jump height (for example, longer ground contact times). During repeated jumping tasks when athletes are required to respond to movement perturbations, the RSI may provide a more accurate evaluation of an individual's ability to switch from an eccentric to a concentric action under varying landing conditions. Thus, the 10-second hop including the RSI could be considered a meaningful tool for monitoring plyometric performance after ACLR. However, further research is required to compare the utility of both the 10-second hop and SLDVJ in their ability to identify residual deficits in knee function before confirming the usefulness of these tests in guiding readiness to RTS.

Self-reported measures are frequently included in formalized testing for determining an athlete's readiness to RTS after ACLR. Earlier investigators[17–20] who examined relationships between hop tests and self-reported function have shown variations in which hop tests were associated with self-reported function across the range of studies. In addition, the strength of these relationships was often low to moderate.[17,18,20] In our study, the total IKDC score was not related to 10-second hop performance. Self-reported function is multifactorial,[20] and these data indicated that athletes' overall patient function scores were independent of their ability to execute vertical rebound tasks.

An interesting observation was that mean 10-second hop asymmetry scores for both jump height and RSI were substantially lower than the passing criterion (>90% LSI) recommended for horizontal hop tests to signal discharge from rehabilitation before RTS.[21] These data were supported by previous findings that unilateral vertical jumps produced lower LSI scores than horizontal hops at a range of time points (6–24 months) post-ACLR.[36] Vertical and horizontal hops could therefore be considered distinctly different tasks by virtue of their moderate associations[3] and measures of limb symmetry being task and variable dependent.[37] Furthermore, the fact that the mean asymmetry scores of the control group were also >10% and quartile values for players in Q1 and Q2 also exceeded this cutoff challenges the concept of applying an arbitrary threshold (eg, >90% LSI) across all tests and metrics in both performance and rehabilitation environments.

Differences in performance between vertical and horizontal hopping may, in part, be due to alterations in lower extremity joint contributions. Chang et al[34] noted that the knee-extensor rate of torque development explained 47% of the variance in vertical jump height. Greater involvement of the hip extensors has been observed when assessing horizontal performance measures[38] and horizontal deceleration of the center of mass during jump landings.[39] Conversely, the greatest relative total positive work contributions occurred at the knee during vertical jumps.[40] Propulsive work contributions of the knee were also lower in horizontal (4%) versus vertical (24%) jump tasks.[4] Thus, performance on a rebound task requiring vertical acceleration of the body is likely determined more heavily by knee-extensor function. Due to residual deficits in quadriceps strength negatively affecting drop jump asymmetry in athletic populations after ACLR,[22] the vertical 10-second rebound task may provide an accurate representation of knee joint function and could be used either as an alternative (when time is limited) or in addition to more traditional horizontal hopping protocols.

Our data may be used as normative reference values to guide rehabilitation and determine an individual's state of readiness to RTS. The descriptive statistics provided in Table 1 in combination with the variables we identified as most associated with 10-second hop performance (Table 4) can help clinicians establish clear targets for soccer players. Furthermore, the quartile values in Table 2 offer clinicians a simple method for identifying how their athletes' scores rank against a comparable population and if a player is on track or delayed during his or her rehabilitation. For example, if a participant is approximately 9 months post-ACLR (based on mean time postsurgery of the participants in the current study), with a 10-second hop height for the involved limb of $\leq$8.2 cm, the score would be in the bottom quartile (Q1), reflecting a low level of performance. Conversely, if a player who is 9 months or more after ACLR has an LSI score $>$82.8%, for the RSI, the score would be in the highest quartile (Q4). In this instance, the player's score is greater than expected and he or she could be classified as ahead of schedule. When players appear to underperform relative to expected values, additional investigation is warranted to determine possible explanations for these residual deficits.

When interpreting the results of the current study, readers should consider that we only measured soccer players with ACLR at a single time point; thus, the temporal recovery of the RSI remains unclear. Also, although determining the RSI using an optical measurement system provides an indication of compensatory strategies, we did not assess movement competency. Previous researchers[1,6] found that performance outcomes (hop distance or time) may suggest acceptable symmetry between limbs; however, these measures do not account for movement quality, which may remain impaired. Recent improvements in wearable technology offer feasible options for clinicians to make more informed and objective decisions. Therefore, other factors relating to neuromuscular control should also be measured and form part of the RTS decision-making process. Further research is warranted to examine these approaches more fully, but we feel this area of research provides an exciting development.

PRACTICAL APPLICATIONS

Lower-level performances and greater asymmetry in 10-second hop performances were seen in soccer players who were in the later stages of rehabilitation after ACLR versus matched control participants. Some of these differences may be attributed to residual deficits in knee-extension and reactive strength as indicated by their predictive associations and the observed between-limbs differences in SLDVJ RSI and isokinetic quadriceps peak torque. Thus, we advise practitioners to train these qualities when appropriate as part of a well-structured reconditioning program with the goal of returning athletes to sport. Finally, greater asymmetry scores during the 10-second hop test ($\sim$25%) than previous values suggested for acceptable discharge from rehabilitation in traditional horizontal hop tests (ie, $>$90% LSI) may indicate that vertical rebound tasks are more sensitive in their ability to identify deficits in knee function after ACLR.

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