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Countermovement Jump and Isokinetic Dynamometry as Measures of Rehabilitation Status After Anterior Cruciate Ligament Reconstruction

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Context: Despite an increase in the literature, few definitive guidelines are available to determine when an athlete has been fully rehabilitated after anterior cruciate ligament reconstruction (ACLR).

Objective: To examine countermovement jump and isokinetic dynamometry measures to (1) identify which measures can best distinguish between ACLR and control participants and (2) provide normative values for identified measures in young adult male multidirectional field-sport athletes.

Design: Cross-sectional study.

Setting: Orthopaedic hospital.

Patients or Other Participants: Young adult male multidirectional field-sport athletes (n = 118) who had undergone unilateral patellar-tendon graft ACLR at least 6 months earlier and healthy male participants (n = 44) with no previous knee injury.

Intervention(s): Single-legged countermovement jump (SL CMJ).

Main Outcome Measure(s): Three-dimensional biomechanical analysis of the SL CMJ and mean peak concentric knee-extension and -flexion torque using isokinetic dynamometry (ISO) were compared in the 2 groups. A stepwise logistic regression was carried out to identify the best predictors of ACLR- or control-group membership (SL CMJ height, limb symmetry index, peak power, joint power contribution, ISO peak torque, limb symmetry index variables).

Results: The control group differed strongly from the ACLR group in isokinetic knee-extension peak torque ($d = -1.33$), SL CMJ performance ($d > 0.4$), and limb symmetry measures in both ISO and jump outcomes ($d > 1.1$). The combination of measures from both ISO and SL CMJ identified group membership with an accuracy of 89%.

Conclusions: Rehabilitation of ACLR patients may be complete when they achieve isokinetic knee-extension peak torque of 260% (±40%) body mass, SL CMJ performance of >17 cm (±4 cm), and reach-limb symmetry measures of >90% in both strength and jump outcomes. The outcomes in the control group can inform return-to-play criteria for young adult male multidirectional field-sport athletes after ACLR.

Key Words: strength, power, knee

Key Points

- The measures that indicate successful rehabilitation after anterior cruciate ligament reconstruction (ACLR) have not been established.
- A combination of isokinetic knee-extension peak torque and single-legged countermovement jump performance measures differentiated between the ACLR and control groups with an accuracy of 89%.
- After ACLR, young adult male athletes should aim to achieve isokinetic knee-extensor peak torque of 260% (±40%) of their body mass, single-legged countermovement jump performance of >17 cm (±4 cm), and reach-limb symmetry measures of >90% in both strength and jump outcomes before rehabilitation is complete and return to play is permitted.

After anterior cruciate ligament (ACL) reconstruction (ACLR) and before return to play, restoring neuromuscular function to optimal levels is the focus of rehabilitation. However, return to play after ACLR is not guaranteed; only 50% to 75% of athletes who underwent ACLR returned to the same level of sport participation,[1–3] and those athletes who returned to play had a high risk of reinjury (ranging from 13.9% to 29.5%).[4–6] Numerous reasons for this increased risk have been proposed, including incomplete rehabilitation, younger age, and returning to a higher level of sport.[4,6] Furthermore, individuals returning to high-impact activities without optimal neuromuscular control may place themselves at higher risk of early osteoarthritis.[7] Consequently, it is important to ensure that an athlete's levels of function have been appropriately restored before returning to sport.

For clinicians making return-to-play decisions, evidence[8,9] suggests that knee-extensor strength, assessed via isokinetic dynamometry (ISO), is associated with the rehabilitation outcome. An ISO device measures the torque produced at a given angle of a single joint and hence can assess knee-extensor and -flexor strength after ACLR.[10] Yet the utility of ISO tests for determining when a safe return to play is possible has been challenged, as only weak relationships with functional performance tests have been identified.[11] As such, the value of the ISO test might be limited because its single-plane nature is contrary to movements in field sports, which are commonly multidirectional and require the simultaneous coordination of multiple joints in multiple planes.[12] Power production as measured during a jumping task is a key measure of athleticism, especially in multidirectional sports.[13] Variables that capture the interaction of joints (eg, percentage of power generation contribution at each joint) during jumping or landing may be better measures for assessing the status of rehabilitation,[9,14–18] as these can identify adaptations in the limbs and joints and interdependent relationships during functional tasks after ACLR.[19] The single-legged (SL) countermovement jump (CMJ) was the most sensitive and valid jump test for assessing restoration of normal function after ACLR[20]; when comparing limbs, jump height was particularly relevant.[21]

Regardless of the task assessed, symmetry between the operated and nonoperated limb is a frequently used indicator of rehabilitation status. Asymmetry of 10% to 15% has been proposed as a return-to-play criterion on both the ISO and SL CMJ tests.[15] However, use of the nonoperated limb as a reference in patients after ACLR[22,23] may be limited because the nonoperated limb may also display reduced strength and power.[24] Values for the most common ISO test protocol (60/60)[25] and symmetry measures in SL CMJ jump height for a healthy cohort have not been reported, although healthy participants also exhibited limb asymmetries in ISO dynamometry tests and functional tasks.[26–28] To assess symmetry, previous authors[28–30] have typically used the limb symmetry index (LSI; equation 1) in ISO testing and functional tests for the dominant and operated leg in healthy and ACL-deficient participants, respectively.

$$\mathrm{LSI} = \left(\frac{\mathrm{Operated}}{\mathrm{Nonoperated}}\right) \times 100 \qquad (1)$$

This approach presents a challenge when comparing ACLR patients with normative individuals because the equation cannot be standardized. The patients may have ruptured the ACL in either the dominant or nondominant limb. This may present a problem in deciding whether the control nondominant limb should be substituted for the operated (see equation 1) and the control dominant for the nonoperated limb or vice versa. Each choice will result in different LSI values. As such, assessing the symmetry using a modified LSI ($\mathrm{LSI}_{\mathrm{modified}}$; equation 2) might be more appropriate.

$$\mathrm{LSI}_{\mathrm{modified}}\sqrt{(100 - \mathrm{LSI})^2} \qquad (2)$$

When judging rehabilitation status, we can use normative values as a reference to determine if a patient is fully rehabilitated after ACLR, ie, his or her scores fall within normal limits. To date, no researchers have examined which measure or combination of measures (from ISO and SL CMJ) can best distinguish between patients after ACLR and control participants as an accurate objective measure of rehabilitation status.

The primary aim of our study was to assess which measures can best distinguish between ACLR and healthy (control) participants. The secondary aim was to provide normative values for use of these measures as return-to-play criteria in young adult male multidirectional field-sport athletes after ACLR.

METHODS

Setting and Participants

This study was carried out in an orthopaedic private hospital at which more than 700 ACL surgical reconstructions take place each year. The hospital's research and ethics committee approved this study (25-AFM-010), which was registered at Clinicaltrials.gov (NCT02771548).

All male multidirectional field-sport athletes aged 24 to 26 years who attended a surgical consultation at least 6 months after ACLR were invited to participate. The ACLR group comprised 118 patients, from October 2013 to March 2014, who met the inclusion criteria and gave informed consent. Inclusion criteria were being male and having undergone primary ACLR surgery using a patellar-tendon graft carried out by a single surgeon. Excluded were individuals who met any of the following criteria: being female or having experienced a concomitant knee fracture or undergone other knee-ligament reconstruction, revision of a previous ACLR, or a previous contralateral ACLR.

Healthy male participants (n = 44) from a multidirectional sport with no history of lower limb injury were recruited as controls. For the purpose of this study, *multidirectional sports* included organized sports that require movements in multiple planes and multiple directions that can be random and reactive in nature—forward, backward, and side to side.

Testing Procedure

An 8-camera motion-analysis system (200 Hz; model Bonita B10; Vicon Motion Systems, Hauppauge, NY), synchronized with two 40- × 60-cm force platforms (1000 Hz; model BP400600; Advanced Mechanical Technology Inc, Watertown, MA), was used to collect the kinematic and kinetic data of the SL CMJ. Data were sampled to 200 Hz, and the Vicon Plug-in-Gait marker set was used as described by Marshall et al.[31] The inverse-dynamics approach was used to calculate joint kinetics.[31]

The athlete's height (m), mass (kg), and operated limb were recorded before testing began. The SL CMJ was assessed first, followed by ISO, and the nonoperated limb was tested first for both. Before jump testing, participants performed a standardized warm-up that consisted of 5 double-legged squats and 2 submaximal double-legged CMJs, followed by 2 submaximal SL CMJs on the leg to be tested. The participants were instructed to stand with 1 foot on the force plate and the free leg behind at approximately 90°. With their hands on their iliac crests, they were asked to complete an SL CMJ, jumping as high as possible. The SL CMJ has high test-retest reliability in patients with ACLR (intraclass correlation coefficient = 0.86–0.97).[32]

Although 3 trials were recorded on each leg, we analyzed only the highest jump. Jump height was determined using

Table 1. Participant Demographics

Variable	Group		P Value
	Anterior Cruciate Ligament Reconstruction	Control	
n	118	44	
	Mean ± SD (95% Confidence Interval)		
Age, y	23.6 ± 5.8 (22.5, 24.6)	24.1 ± 3.6 (23.5, 24.7)	.663
Height, cm	182.6 ± 6.7 (180.3, 184.9)	183.1 ± 6.5 (181.2, 185.1)	.477
Body mass, kg	81.9 ± 10.5 (80.0, 83.8)	82.7 ± 8.0 (80.3, 85.2)	.300
Time since surgery, mo	6.6 ± 1.0 (6.4, 6.8)	–	–
Self-reported function (International Knee Documentation Committee form)	68.3 ± 8.9 (66.6, 70.1)	–	–

the impulse-momentum relationship.[11] Jump height represents an index of muscle power that is independent of body size; thus, the recorded heights (cm) of vertical jumps were not normalized to body mass.[33] Maximum power (peak power) was measured and normalized to body weight during the propulsion phase of the SL CMJ. Power generated at the hip, knee, and ankle joint in the sagittal plane was expressed as a percentage of total peak power (sum of all 3 joints) during the propulsion phase of the SL CMJ. We chose peak power because, in contrast to peak moment, peak power has a strong relationship ($r > 0.72$) with jump height.[34,35]

After jump testing was conducted, concentric knee-extension and -flexion peak torque were assessed at an angular velocity of 60°/s using an ISO dynamometer (model Cybex Norm; Computer Sports Medicine Inc, Stoughton, MA). High relative reliability and moderate absolute reliability have been found for measuring peak-torque values of concentric knee extension at 60°/s using the Cybex Norm.[36] The participants first performed a warm-up set that consisted of 5 repetitions of extension and flexion at 50% to 75% and 1 attempt at 100% of maximal effort. After a 60-second rest period, the athletes were then instructed to complete 2 maximal-extension and -flexion sets of 5 repetitions. They were instructed to push and pull as hard and fast as possible against the resistance. The procedure was then repeated on the operated limb. The set with the lowest coefficient of variance was analyzed. Knee-extension and -flexion peak torques normalized to body mass ($\mathrm{Nm \cdot kg^{-1}}$) and LSI were the primary variables of interest.

Descriptive statistics are presented as mean ± standard deviation and 95% confidence interval (CI) where applicable. Paired-samples *t* tests were carried out to detect statistical differences between the operated and nonoperated limbs, and an independent-samples *t* test was conducted between groups. When testing between groups for differences in non-LSI measures, the operated limb of the ACLR group was compared with the dominant limb (kicking leg) of the control group. The SL CMJ height (cm), peak power, joint power contributions, LSI, and LSI$_{\text{modified}}$ were compared between limbs and groups. The ISO variables analyzed were knee-extension and -flexion peak torque as a percentage of body mass, LSI, and LSI$_{\text{modified}}$; LSI and LSI$_{\text{modified}}$ were calculated according to equations 1 and 2 shown earlier. To examine the effect of statistical differences, the Cohen d was calculated and classified as *small* (0.20–0.49), *moderate* (0.50–0.79), or *large* ($\geq$0.80).[37] To examine the probability of committing a type II error during the analysis and find the smallest statistically significant difference that would have been detectable with the given sample size, we performed a post hoc power analysis.

A stepwise logistic regression enabled us to identify the combination of variables, using features of (1) the ISO test, (2) the SL CMJ, and (3) both exercises to most accurately model the response variable (ACLR = 0 or control = 1). To robustly examine which features should be included in a regression model, we repeated the stepwise logistic regression process 100 times using different randomly selected participants' training data (108 ACLR and 34 control). Features that were chosen more than 50 times were used as input variables for a multinomial regression model, which was fit to a randomized training set (108 ACLR and 34 control) and subsequently used to predict the group membership of a testing set (10 ACLR and 10 control). The accuracy of the model was assessed by comparing predicted to actual membership. The process was repeated 100 times using different randomly selected participants' training data and testing sets to achieve a robust measure of the expected accuracy. Coefficients and intercepts were averaged to describe the prediction function.

Significance was set at $P < .05$. Data processing and descriptive statistics were carried out using MATLAB (version R2015a; The MathWorks Inc, Natick, MA).

RESULTS

Demographics did not differ between the healthy and ACLR cohorts (Table 1). The ACLR participants had undergone surgery an average of 6.6 ± 1.0 months earlier. The statistical power was 0.95 or greater for all significantly different measures, with effect sizes greater than 0.5.

Between-Limbs Differences

Between limbs of the ACLR group, all ISO and SL CMJ measures were different except for the percentage of ankle power contribution. With the exception of the percentage of hip power contribution, which was higher, the operated limb demonstrated smaller values (Table 2). Based on effect size, the order of the differences from highest to lowest was ISO knee-extension peak torque (d = –1.33), SL CMJ hip power contribution (d = 0.75), SL CMJ height (d = –0.71), SL CMJ peak power (d = –0.47, $\beta = 0.99$), SL CMJ

Table 2. Physical Performance Measures

	Group						
	Anterior Cruciate Ligament Reconstruction (n = 118)			Control (n = 44)			
	Limb, Mean ± SD		Between-Limbs Differences *P* Value (Cohen d)	Limb, Mean ± SD		Between-Limbs Differences *P* Value (Cohen d)	Between-Groups Differences *P* Value (Cohen d)
Measure	Operated	Nonoperated		Dominant	Nondominant		
Isokinetic							
Knee-extension peak torque							
%BM	200.2 ± 44.9	260.1 ± 45.3	<.001 (–1.33)	260.8 ± 37.2	253.3 ± 39.7	.022 (0.20)	<.001 (–1.20)
LSI	77.3 ± 13.6			103.6 ± 9.1			<.001 (–1.53)
$LSI_{modified}$	23.6 ± 11.9			6.9 ± 6.9			<.001 (1.28)
Knee-flexion peak torque							
%BM	145.7 ± 28.5	151.2 ± 28.1	<.001 (–0.19)	155.9 ± 24.3	154.9 ± 22.6	.677 (0.04)	.038 (–0.36)
LSI	96.9 ± 12.3			101.0 ± 10.2			.050 (–0.35)
$LSI_{modified}$	9.7 ± 8.2			8.2 ± 6.0			.279 (0.19)
Single-legged countermovement jump height							
cm	13.1 ± 4.0	16.0 ± 4.1	<.001 (–0.71)	17.0 ± 4.1	17.1 ± 4.1	.64 (0.02)	<.001 (–0.86)
LSI	82.0 ± 12.0			99.9 ± 11.5			<.001 (–1.12)
$LSI_{modified}$	20.2 ± 12.0			7.8 ± 8.3			<.001 (1.12)
Single-legged countermovement jump power							
Watt·kg–1	3393.8 ± 678.6	3724.4 ± 720.6	<.001 (–0.47)	3828.5 ± 659.3	4006.7 ± 715.8	<.001 (–0.26)	<.001 (–0.58)
LSI	91.5 ± 9.9			96.0 ± 7.4			.007 (–0.51)
$LSI_{modified}$	10.7 ± 7.6			6.8 ± 5.0			.002 (0.61)
Proportion of power, %							
Hip	22.7 ± 5.7	18.6 ± 5.3	<.001 (0.75)	19.3 ± 4.8	20.0 ± 4.8	.340 (–0.15)	<.001 (0.61)
Knee	28.8 ± 12.3	33.1 ± 10.7	.003 (–0.37)	33.5 ± 9.8	33.8 ± 7.3	.482 (–0.03)	.024 (–0.40)
Ankle	48.5 ± 10.1	48.3 ± 9.5	.876 (0.02)	47.2 ± 8.4	46.2 ± 5.8	.708 (0.14)	.482 (0.12)

Abbreviations: LSI, limb symmetry index (equation 1, $LSI_{modified}$: equation 2); %BM, percentage body mass (ie, variable/body mass × 100).

Table 3. Stepwise Logistic Regression Analysis Results and Equations, %

Regression	Equation	Group		Accuracy
		Misclassification Control	Anterior Cruciate Ligament	
All variables	–1.0092 + (Proportion of power hip × 0.15243) + (ISO knee-extensor peak torque %BM × –2.0582) + (Knee-extensor $\text{LSI}_{\text{modified}}$ × 0.21182) + (SL CMJ height $\text{LSI}_{\text{modified}}$ × 0.10168)	2.8	8.1	89.2[a]
ISO variables	4.1709 + (ISO knee-extensor peak torque %BM × –2.3621) + (ISO knee-extensor $\text{LSI}_{\text{modified}}$ × 0.20465)	3.7	11.8	84.6
SL CMJ variables	–1.3402 + (SL CMJ height [cm] × 0.17651) + (Proportion of power hip [%] × 0.16672) + (SL CMJ height $\text{LSI}_{\text{modified}}$ × 0.1266)	4.5	22.4	74.7

Abbreviations: %BM, percentage body mass (ie, variable/body mass × 100); LSI, limb symmetry index; SL CMJ, single-legged countermovement jump.

[a] Sensitivity = 93.9% (95% confidence interval = 92%, 96%); specificity: 81.5% (95% confidence interval = 79%, 84%).

knee power contribution ($d = -0.37$, $\beta = 0.97$), and ISO knee-flexion peak torque ($d = -0.19$, $\beta = 0.54$).

In the control group, only 2 measures were different. The SL CMJ peak power was higher for the nondominant limb ($d = -0.26$, $\beta = 0.41$), while the ISO knee-extension peak torque was larger for the dominant limb ($d = 0.20$, $\beta = 0.25$). The control group displayed no differences between limbs at the hip, knee, or ankle ($P > .05$, Cohen $d < 0.15$) in proportion of power generation, with a similar distribution evident in the nonoperative limb of the ACLR group.

Between-Groups Differences

Between-groups differences were significant for all ISO measures except for knee-flexion peak torque $\text{LSI}_{\text{modified}}$. Based on effect size, the order of the differences from highest to lowest was ISO knee-extension LSI ($d = -1.53$), $\text{LSI}_{\text{modified}}$ ($d = 1.28$), ISO knee-extension peak torque ($d = -1.20$), SL CMJ height LSI ($d = -1.12$), SL CMJ height ($d = -0.86$), SL CMJ peak power $\text{LSI}_{\text{modified}}$ ($d = -0.61$), hip power contribution ($d = 0.61$), SL CMJ knee power contribution ($d = -0.40$, $\beta = 0.70$), and ISO knee-flexion peak torque ($d = -0.36$, $\beta = 0.64$).

Logistic Regression

The stepwise logistic regression identified the following variables as most appropriate for predicting group membership: percentage of hip power contribution, ISO knee-extension peak torque, knee-extension $\text{LSI}_{\text{modified}}$, and SL CMJ height $\text{LSI}_{\text{modified}}$. A detailed description can be found in Table 3. The results of the logistic regression suggest that a combination of variables from ISO and SL CMJ testing can best predict group membership (89.2%), followed by the ISO model (84.6%) and the SL CMJ value (74.7%).

Normative Values

Normative values and 95% CIs are reported for the ISO and SL CMJ variables in Table 4. In the control group, ISO knee-extension peak torque was 261% of body mass in the dominant and 253% in the nondominant limb. The ISO knee-flexion peak torque was a mean of 155% of body mass in both limbs. Healthy participants jumped a mean of 17 cm using either limb. The distribution of extension power generation in the control group (rounding to the nearest 10%) was 20% hip, 30% knee, and 50% ankle bilaterally. Limb symmetry indices were approximately 100% for SL CMJ height, 96% for peak power, and 104% for ISO knee-extension and 101% for ISO knee-flexion peak torques, with standard deviations of approximately 10% for these healthy participants.

DISCUSSION

The normative (control) cohort differed strongly from the ACLR group in ISO knee-extension LSI, ISO knee-extension $\text{LSI}_{\text{modified}}$, ISO knee-extension peak torque, SL CMJ height LSI, and SL CMJ height, whereas the combination of proportion of power at the hip, ISO knee-extension peak torque, knee-extension $\text{LSI}_{\text{modified}}$, and SL CMJ height $\text{LSI}_{\text{modified}}$ identified group membership with an accuracy of 89%. These results may help us to determine which tests and variables most accurately identify rehabilitation deficits after ACLR.

Isokinetic Dynamometry

The ACLR group demonstrated large limb asymmetries in ISO knee-extension peak torque, while the control group displayed small but significant asymmetries. The effect size between limbs in the control group ($d = 0.20$) was small.[37] The largest effect size was between groups in ISO knee-extension peak torque for magnitude, LSI, and $\text{LSI}_{\text{modified}}$. Small but significant differences were present between groups in ISO knee-flexion peak torque variables, which will not be discussed due to its high probability of type II error ($\beta = 0.64$).

The ISO knee-extension peak-torque LSI demonstrated the largest effect size and, accordingly, was the most sensitive measure to differences between the ACLR and control groups. Interestingly, the control group also demonstrated a difference between limbs in knee-extension peak torque and symmetry, so it may be important to look at other variables when assessing readiness to return to play. These findings confirm the value of examining knee-extension peak-torque symmetry as a measure of rehabil-

Table 4. Normative Values With Confidence Intervals

	Limb Normative Data (n = 44)	
	Mean ± SD (95% Confidence Interval)	
	Dominant	Nondominant
Isokinetic		
Knee-extension peak torque		
%BM	260.8 ± 37.2 (249, 272)	253.3 ± 39.7 (241, 265)
LSI	103.6 ± 9.1 (100.8, 106.4)	
LSI$_{\text{modified}}$	6.9 ± 6.9 (4.8, 9.0)	
Knee-flexion peak torque		
%BM	155.9 ± 24.3 (148, 163)	154.9 ± 22.6 (148, 162)
LSI	101.0 ± 10.2 (97.9, 104.1)	
LSI$_{\text{modified}}$	8.2 ± 6.0 (6.4, 10.0)	
Single-legged countermovement height		
cm	17.0 ± 4.1 (15.8, 18.2)	17.1 ± 4.1 (15.9, 18.4)
LSI	99.9 ± 11.5 (96.4, 103.4)	
LSI$_{\text{modified}}$	7.8 ± 8.3 (5.3, 10.3)	
Single-legged countermovement power		
Watt·kg–1	3828.5 ± 659.3 (3628.1, 4029.0)	4006.7 ± 715.8 (3789.1, 4224.4)
LSI	96.0 ± 7.4 (93.8, 98.2)	
LSI$_{\text{modified}}$	6.8 ± 5.0 (5.3, 8.3)	
Proportion of power, %		
Hip	19.3 ± 4.8 (17.8, 20.8)	20.0 ± 4.8 (18.6, 21.5)
Knee	33.5 ± 9.8 (30.5, 36.5)	33.8 ± 7.3 (31.6, 36.0)
Ankle	47.2 ± 8.4 (44.7, 49.8)	46.2 ± 5.8 (44.4, 47.9)

Abbreviations: %BM, percentage body mass (ie, variable/body mass × 100); LSI, limb symmetry index.

itation status and may be used to guide ACLR rehabilitation.[9,15,17]

Single-Legged Countermovement Jump

The ACLR group demonstrated large limb asymmetries in SL CMJ height, whereas no difference was found between limbs in the control group. Large effect sizes were present between groups for SL CMJ height, LSI, and LSI$_{\text{modified}}$. Moderate differences occurred between groups for SL CMJ peak power. Control participants displayed symmetry in jump height and joint power generated in both limbs, indicating that symmetric measures will be important in assessing completion of rehabilitation.

The athletes with ACLR differed from healthy athletes in the percentage of power per joint. A higher proportion of peak power was generated through the hip in the ACLR group's operated limb compared with both their nonoperated limbs and the control group. This reduction at the knee suggests a redistribution of effort to the hip during the SL CMJ in the operated limbs. Joint power generation at the knee was previously shown[19] to be reduced in the stance phase of running, which suggests that after ACLR, load distribution may be altered during functional movements.

The difference in power distribution may be related to the lower strength values identified in the ACLR group compared with their healthy counterparts. We conducted a post hoc Pearson correlation to examine the relationship between ISO strength and the power generation at each joint in the ACLR and control groups (Table 5). The distribution of power generation across the hip, knee, and ankle joints was positively correlated with ISO knee-extension peak torque in the ACLR group (Pearson $r =$ 0.28–0.31, $P < .002$), but no significant correlation was found between these factors in the control group ($P > .05$). This may indicate that strength has a small association with extension power generation distribution across the lower limb joints after ACLR.

Our findings suggest that operated limbs may compensate for lower peak power generation at the knee by generating a higher proportion of power at the hip during jumping. Previous investigators[38] determined that the hip or ankle extensors compensated for a knee-extension deficit in vertical jump landing, where differences between operated and nonoperated limbs may predispose people to a risk of injury. It is important to note, however, that participants in their study completed a CMJ with arm swing, whereas those in our study did not, potentially influencing the jumping and landing mechanics.

Table 5. Bivariate Correlations Between Isokinetic Knee-Extensor Peak Torque and the Proportion of Peak Power Generation During the Jump Phase of the Single-Legged Countermovement Jump

	Group Knee-Extension Peak Torque, Nmkg^{-1}			
	Anterior Cruciate Ligament Reconstruction (n = 118)		Control (n = 44)	
Proportion of power, %[a]	Pearson Correlation	*P* Value	Pearson Correlation	*P* Value
Hip	0.310	.001	0.104	.500
Knee	0.279	.002	0.042	.788
Ankle	0.310	<.001	0.139	.369

[a] Outcome as measured in the operated limb and the dominant limb of the anterior cruciate ligament reconstruction and control groups, respectively.

Logistic Regression

The stepwise logistic regression identified the ISO measures of knee-extension peak torque relative to body mass and $LSI_{modified}$ as well as jump height and proportion of power generated at the hip in SL CMJ as the most important predictors of ACLR- or control-group membership (89% accuracy; Table 3). With ISO measures alone, the accuracy was 84.6%; with SL CMJ measures alone, the accuracy was 74.7%.

Although ISO knee-extension LSI had the largest between-groups difference (Cohen d = –1.53), the regression analysis selected its modified version. One possible reason might be that the LSI measurement does not account for operated, nonoperated, dominant, or nondominant limb, which could have artificially inflated the effect sizes for the LSI values. Such effects may have been removed due to the repetitive regression analysis using different datasets.

In this model, the first selected predictor was percentage of hip power generation in jumping. Assessing single-plane ISO strength in a single joint and a single muscle group, such as the quadriceps, is important for identifying a fully rehabilitated athlete; however, assessing functional tasks allows investigators to observe movement in a dynamic manner, similar to the activities anticipated on return to play.

We acknowledge that although strength and power are important, these 2 factors alone do not tell the whole story. This logistic regression did not take into account motor control at multiple joints of the lower limb or the interaction of the trunk during the jumping task. Screening tools such as the Landing Error Scoring System[39] and tuck jump[15] are inexpensive and easy-to-use field tests that aim to identify this compensation at the hip by looking for poor movement patterns. However, quantifying the limitation in joint power and strength may enhance the assessment of rehabilitation status after ACLR and add to the specific, measurable, and individualized targets and goals that patients can aim to achieve postoperatively.

Normative Values

Absolute values were recorded for the control group in this study, allowing estimation of appropriate targets for male patients in the 24- to 26-year-old age group after ACLR. Based on the reported 95% CIs, these participants should be able to jump between 16 cm and 18 cm to be considered recovered. They should achieve 240% to 270% of their body mass on ISO knee-extension testing and 150% to 160% of their body mass on ISO knee-flexion testing. These results also confirm accepted practice with regard to symmetry: aiming for greater than 90% of the opposite limb in both strength and functional testing outcomes.[9,15,17] Power generation in the control group demonstrated no between-limbs differences, while the ACLR group demonstrated a higher percentage of power at the hip in the operated limb than in the nonoperated limb, which showed a similar distribution as in the healthy limbs. This finding, further compounded by the identification of hip-joint power as the strongest predictor of group membership, highlights the importance of examining jumping strategy and jumping height when assessing rehabilitation status.

Although these results indicate that limb symmetry is important, absolute values in the ACLR limbs did not correlate with those in our control group. We could postulate that nonoperated limbs lose strength and power postoperatively,[26] yet in these participants, the nonoperated limb demonstrated strength and power values similar to those in the control group.

The normative values identified in this study add to the literature and offer relative measures that athletes can target as markers of normal function. Normative values can be used as return-to-play criteria, whereby clinicians can be assured that ACLR patients have achieved strength and power that are normal for their age, sex, and activity level, even if the limb strength and performance outcomes are symmetric.

Limitations and Considerations

Our study was limited to active males between 24 and 26 years of age. Furthermore, the number of control participants was small. Future authors should aim to establish more generalizable normative values for commonly used outcome measures in ACLR rehabilitation specific to each sex and activity level.

It was also beyond the scope of this study to detail the individual rehabilitation course of each participant, which may be a confounding variable for both the ACLR and control group results. Although all in the ACLR group had undergone surgery at least 6 months earlier, their recovery experiences may have been different. We did not account for how long each participant had been allowed to perform jumping activities. Those who had been cleared more recently may have had poorer jump heights than individuals who had been cleared earlier and had more time to practice and perform this task.

Specific variations in movement patterns between sexes during the early landing phase after a jump have been well established[40,41]; thus, we deemed it important to include only male participants. The current study results should therefore not be generalized to female athletes.

Six months postsurgery was chosen as an appropriate time for assessment in this study, when subjective knee function is well below normative values. This can be supported by an average score of 68.3 on the International Knee Documentation Committee form (95% CI = 66.6, 70.1) for the ACLR group. For a normative population of men aged 18 to 24 years with no history of knee problems, a score of 89 ± 18 according to the International Knee Documentation Committee has been established.[42] This suggests that the rehabilitation within the ACLR group in this study was not complete at the 6-month postoperative testing and is an important consideration when interpreting our results.

We performed multiple comparisons, and one could argue that we should have implemented a multiple-comparisons correction to reduce the type 1 error. However, as the type I error decreases, the chance of type II errors increases.[43–46] Our conclusions were based on *P* values in combination with effect sizes, and differences with weak effects were handled with care. The reader should note that some significant differences with weak effect sizes would not have been different if we had applied a correction (ie, ISO knee-extension peak torque in the control group and ISO knee-flexion peak torque, SL CMJ peak power LSI, and proportion of power generated at the knee between the ACLR and control groups).

CONCLUSIONS

Considering both SL CMJ and ISO strength measures is important when assessing a patient's rehabilitation status after ACLR. The normative and ACLR cohorts differed strongly in absolute and symmetry measures but also in jumping strategies, with increased hip power compensating on the reconstructed side. This was supported by the results of a repetitive regression analysis that determined group membership with 89% accuracy by selecting absolute and symmetry measures of SL CMJ and ISO. As such, measuring absolute strength and performance during both a multijoint closed chain activity as well as ISO strength is beneficial in identifying the athlete's needs during rehabilitation.

Future authors should examine the biomechanical differences between limbs and compare ACLR and healthy participants to identify relevant variables and look prospectively at the influence of strength and power measures on return to play and the risk of a second ACL injury.

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REFERENCES

1. 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.
2. McCullough KA, Phelps KD, Spindler KP, et al. Return to high school- and college-level football after anterior cruciate ligament reconstruction: a Multicenter Orthopaedic Outcomes Network (MOON) cohort study. *Am J Sports Med*. 2012;40(11):2523–2529.
3. Brophy RH, Schmitz L, Wright RW, et al. Return to play and future ACL injury risk after ACL reconstruction in soccer athletes from the Multicenter Orthopaedic Outcomes Network (MOON) group. *Am J Sports Med*. 2012;40(11):2517–2522.
4. Failla M, Logerstedt D, Grindem H, et al. Outcomes 2 years after ACLR in athletes: function, return to sport rates, and re-injury rates from the Delaware-Oslo ACL cohort study. *Orthop J Sports Med*. 2015;3(suppl 2). doi: 10.1177/2325967115S00029.
5. Wiggins AJ, Grandhi RK, Schneider DK, Stanfield D, Webster KE, Myer GD. Risk of secondary injury in younger athletes after anterior cruciate ligament reconstruction: a systematic review and meta-analysis. *Am J Sports Med*. 2016;44(7):1861–1876.
6. Paterno MV, Rauh MJ, Schmitt LC, Ford KR, Hewett TE. Incidence of second ACL injuries 2 years after primary ACL reconstruction and return to sport. *Am J Sports Med*. 2014;42(7):1567–1573.
7. Culvenor AG, Crossley KM. Accelerated return to sport after anterior cruciate ligament injury: a risk factor for early knee osteoarthritis? *Br J Sports Med*. 2016;50(5):260–261.
8. Keays SL, Bullock-Saxton JE, Newcombe P, Keays AC. The relationship between knee strength and functional stability before and after anterior cruciate ligament reconstruction. *J Orthop Res*. 2003;21(2):231–237.
9. Kvist J. Rehabilitation following anterior cruciate ligament injury: current recommendations for sports participation. *Sports Med*. 2004;34(4):269–280.
10. Xergia SA, Pappas E, Zampeli F, Georgiou S, Georgoulis AD. Asymmetries in functional hop tests, lower extremity kinematics, and isokinetic strength persist 6 to 9 months following anterior cruciate ligament reconstruction. *J Orthop Sports Phys Ther*. 2013;43(3):154–162.
11. Richter C, O'Connor NE, Marshall B, Moran K. Analysis of characterizing phases on waveform: an application to vertical jumps. *J Appl Biomech*. 2014;30(2):316–321.
12. Knezevic OM, Mirkov DM, Kadija M, Milovanovic D, Jaric S. Evaluation of isokinetic and isometric strength measures for monitoring muscle function recovery after anterior cruciate ligament reconstruction. *J Strength Cond Res*. 2014;28(6):1722–1731.
13. Delaney JA, Scott TJ, Ballard DA, et al. Contributing factors to change-of-direction ability in professional rugby league players. *J Strength Cond Res*. 2015;29(10):2688–2696.
14. Dauty M, Le Brun J, Huguet D, Paumier S, Dubois C, Letenneur J. Return to pivot-contact sports after anterior cruciate ligament reconstruction: patellar tendon or hamstring autografts [in French]. *Rev Chir Orthop Reparatrice Appar Mot*. 2008;94(6):552–560.
15. Myer GD, Paterno MV, Ford KR, Quatman CE, Hewett TE. Rehabilitation after anterior cruciate ligament reconstruction: criteria-based progression through the return-to-sport phase. *J Orthop Sports Phys Ther*. 2006;36(6):385–402.
16. Myklebust G, Bahr R. Return to play guidelines after anterior cruciate ligament surgery. *Br J Sports Med*. 2005;39(3):127–131.
17. Neeter C, Gustavsson A, Thomeé P, Augustsson J, Thomeé R, Karlsson J. Development of a strength test battery for evaluating leg muscle power after anterior cruciate ligament injury and reconstruction. *Knee Surg Sports Traumatol Arthrosc*. 2006;14(6):571–580.
18. 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.
19. Devita P, Hunter PB, Skelly WA. Effects of a functional knee brace on the biomechanics of running. *Med Sci Sports Exerc*. 1992;24(7):797–806.
20. Gustavsson A, Neeter C, Thomeé P, et al. A test battery for evaluating hop performance in patients with an ACL injury and patients who have undergone ACL reconstruction. *Knee Surg Sports Traumatol Arthrosc*. 2006;14(8):778–788.
21. Nyland J, Klein S, Caborn DN. Lower extremity compensatory neuromuscular and biomechanical adaptations 2 to 11 years after anterior cruciate ligament reconstruction. *Arthroscopy*. 2010;26(9):1212–1225.
22. Thomeé R, Neeter C, Gustavsson A, et al. Variability in leg muscle power and hop performance after anterior cruciate ligament reconstruction. *Knee Surg Sports Traumatol Arthrosc*. 2012;20(6):1143–1151.
23. Pairot de Fontenay B, Argaud S, Blache Y, Monteil K. Contralateral limb deficit seven months after ACL-reconstruction: an analysis of single-leg hop tests. *Knee*. 2015;22(4):309–312.
24. Button K, van Deursen R, Price P. Measurement of functional recovery in individuals with acute anterior cruciate ligament rupture. *Br J Sports Med*. 2005;39(11):866–871.
25. 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.
26. Östenberg A, Roos E, Ekdah C, Roos H. Isokinetic knee extensor strength and functional performance in healthy female soccer players. *Scand J Med Sci Sports*. 1998;8(5, pt 1):257–264.
27. Requena B, González-Badillo JJ, de Villareal ESS, et al. Functional performance, maximal strength, and power characteristics in isometric and dynamic actions of lower extremities in soccer players. *J Strength Cond Res*. 2009;23(5):1391–1401.

28. Wilk KE, Romaniello WT, Soscia SM, Arrigo CA, Andrews JR. The relationship between subjective knee scores, isokinetic testing, and functional testing in the ACL-reconstructed knee. *J Orthop Sports Phys Ther*. 1994;20(2):60–73.
29. Ostenberg A, Roos E, Ekdahl C, Roos H. Isokinetic knee extensor strength and functional performance in healthy female soccer players. *Scand J Med Sci Sports*. 1998;8(5, pt 1):257–264.
30. 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 Relat Res*. 1990;(255):204–214.
31. Marshall BM, Franklyn-Miller AD, King EA, Moran KA, Strike SC, Falvey ÉC. Biomechanical factors associated with time to complete a change of direction cutting maneuver. *J Strength Cond Res*. 2014; 28(10):2845–2851.
32. Hopper DM, Goh SC, Wentworth LA, et al. Test–retest reliability of knee rating scales and functional hop tests one year following anterior cruciate ligament reconstruction. *Phys Ther Sport*. 2002; 3(1):10–18.
33. Markovic G, Jaric S. Is vertical jump height a body size-independent measure of muscle power? *J Sports Sci*. 2007;25(12):1355–1363.
34. Cormie P, McBride JM, McCaulley GO. Power-time, force-time, and velocity-time curve analysis of the countermovement jump: impact of training. *J Strength Cond Res*. 2009;23(1):177–186.
35. Dowling JJ, Vamos L. Identification of kinetic and temporal factors related to vertical jump performance. *J Appl Biomech*. 1993;9(2):95–110.
36. Impellizzeri FM, Bizzini M, Rampinini E, Cereda F, Maffiuletti NA. Reliability of isokinetic strength imbalance ratios measured using the Cybex NORM dynamometer. *Clin Physiol Funct Imaging*. 2008; 28(2):113–119.
37. Cohen J. *Statistical Power Analysis for the Behavioral Sciences*. 2nd ed. Hillsdale, NJ: L. Erlbaum Associates; 1988.
38. Ernst GP, Saliba E, Diduch DR, Hurwitz SR, Ball DW. Lower extremity compensations following anterior cruciate ligament reconstruction. *Phys Ther*. 2000;80(3):251–260.
39. Padua DA, Marshall SW, Boling MC, Thigpen CA, Garrett WE, Beutler AI. The Landing Error Scoring System (LESS) is a valid and reliable clinical assessment tool of jump-landing biomechanics: the JUMP-ACL study. *Am J Sports Med*. 2009;37(10):1996–2002.
40. Chappell JD, Creighton RA, Giuliani C, Yu B, Garrett WE. Kinematics and electromyography of landing preparation in vertical stop-jump: risks for noncontact anterior cruciate ligament injury. *Am J Sports Med*. 2007;35(2):235–241.
41. Ford KR, Myer GD, Hewett TE. Valgus knee motion during landing in high school female and male basketball players. *Med Sci Sports Exerc*. 2003;35(10):1745–1750.
42. 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.
43. Rothman KJ. No adjustments are needed for multiple comparisons. *Epidemiology*. 1990;1(1):43–46.
44. Perneger TV. What's wrong with Bonferroni adjustments. *BMJ*. 1998;316(7139):1236–1238.
45. Hopkins WG, Marshall SW, Batterham AM, Hanin J. Progressive statistics for studies in sports medicine and exercise science. *Med Sci Sports Exerc*. 2009;41(1):3–13.
46. Wasserstein RL, Lazar NA. The ASA's statement on *P* values: context, process, and purpose. *Am Stat*. 2016;70(2):129–133.

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