Journal of Athletic Training 2022;57(9/10):946–954
doi: 10.4085/1062-6050-0636.21

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Identification and Predictors of Age-Relevant and Activity-Relevant Hop Test Targets in Young Athletes After Anterior Cruciate Ligament Reconstruction

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Context: Performance symmetry between limbs (limb symmetry index [LSI] $\geq$ 90%) on a battery of single-leg hop tests is recommended to inform return-to-sport (RTS) decisions after anterior cruciate ligament (ACL) reconstruction (ACLR). Achieving current hop test symmetry values has not been associated with future clinical outcomes. The identification of age-relevant and activity-relevant target values to benchmark the hop test performance of young athletes post-ACLR may provide greater specificity and clinical relevance for interpretation of hop test data.

Objective: To identify single-leg hop test-target values for individual-limb performance and symmetry between limbs for athletes without a history of ACL injury and evaluate the proportion of young athletes post-ACLR who met the newly derived target values at the time of RTS clearance. The secondary objective was to test the hypothesis that better function and strength would be associated with achieving the newly derived hop test target values.

Design: Cross-sectional study.

Setting: Pediatric medical center and academic medical center.

Patients or Other Participants: A total of 159 young athletes (age = 16.9 $\pm$ 2.2 years) at the time of RTS clearance after primary, unilateral ACLR and 47 uninjured control athletes (age = 17.0 $\pm$ 2.3 years).

Main Outcome Measure(s): All participants completed a single-leg hop test battery (single hop, triple hop, and crossover hop for distance [cm], and 6-m timed hop [seconds]). Raw distance values were normalized by body height, and LSI (%) was calculated for each hop test. Target values were defined as the lower bound of the 95% CI for each hop test, using control group data. Participants with ACLR also completed the Knee injury and Osteoarthritis Outcome Score subscales and a quadriceps femoris strength (newton meters/kilogram) assessment. Logistic regression determined predictors of achieving hop test target values in the ACLR group among injury, function, and strength data ($P < .05$).

Results: In the ACLR group, 79% to 84% of participants met the 90% LSI threshold on each hop test. They achieved the target values for surgical-limb performance in the following proportions (% participants): single hop = 29%, triple hop = 24%, crossover hop = 30%, 6-m timed hop = 18%, all hops= 12%. Also, they met the target values for LSI in the following proportions: single hop = 43%, triple hop = 48%, crossover hop = 50%, 6-m timed hop = 69%, all hops = 25%. The only predictor of achieving all hop test targets for surgical-limb performance was greater surgical-limb quadriceps femoris strength (odds ratio = 4.10, $P = .007$). We noted a trend toward quadriceps femoris strength LSI $\geq$ 90% (odds ratio = 2.44, $P = .058$) as a predictor for meeting all hop test symmetry targets.

Conclusions: At the time of RTS post-ACLR, only a small proportion of young athletes achieved the age-relevant and activity-relevant single-leg hop test targets for surgical-limb performance or symmetry between limbs, even though a majority met the traditionally recommended 90% LSI threshold on hop tests.

Key Words: knee, return to sport, functional performance

Key Points

- Benchmarking the hop test performance of young athletes after anterior cruciate ligament (ACL) reconstruction against the newly derived age-relevant and activity-relevant normative performance values, identified from athletes without a history of ACL injury, for individual-limb performance, may better represent the status of functional performance recovery of the surgical limb with the potential to better inform return-to-sports readiness in this vulnerable population, although further work is warranted.
- Greater surgical limb quadriceps femoris strength was associated with higher odds of meeting the single-leg hop target value (as identified from athletes without a history of ACL injury) with the surgical limb.

Anterior cruciate ligament (ACL) injuries are one of the most common sport-related knee injuries among young athletes participating in cutting and pivoting sports. For those who wish to resume high-level activities, ACL reconstruction (ACLR) is often recommended to restore functional joint stability. However, despite restoration of anatomic stability, outcomes varied widely in this young patient population. Although 84% of individuals expected to return to preinjury activities post-ACLR, only 48% of those younger than 25 years old returned to cutting and pivoting sports.[1,2] Among young athletes who did participate in sports post-ACLR, 20% to 30% sustained a second ACL injury,[3–5] with the highest risk early in the first 12 months of return to sport (RTS).[4] These high rates of second ACL injuries in this young population equated to a 30 to 40 times greater risk of an ACL injury than in young athletes without a history of ACL injury.[5] The low RTS rate and high second-injury rate experienced by a substantial portion of young athletes post-ACLR indicate the need for improved RTS guidelines.

Functional performance measures are often used in a clinical setting to inform readiness for RTS, as they represent clinically feasible measures for assessing performance in many settings. A battery of single-leg hop tests—including the single hop for distance, triple hop for distance, crossover hop for distance, and timed 6-m hop—have been established as practical strategies for evaluating functional performance in young athletes post-ACLR.[6] Limb-to-limb differences in performance are typically expressed as a limb symmetry index (LSI; ratio of the involved and uninvolved limb performance $\times$ 100%), with LSI values of $\geq$90% being recommended as the "passing" criterion cutoff value.[6–8] However, a recent study[9] indicated that achieving LSI values of $\geq$90% on single-leg hop tests did not predict longitudinal outcomes of knee function. Further, LSI scores frequently overestimated knee function post-ACLR, which may have been related to diminished performance of the uninvolved limb.[10,11] The shortcomings of current single-leg hop LSI recommendations create the opportunity to provide greater specificity and clinical relevance for interpretation of hop test data. Benchmarking the hop test performance of young athletes post-ACLR against age-relevant and activity-relevant normative performance values for individual-limb performance and symmetry between limbs could overcome the shortcoming of relying only on traditional 90% LSI to inform decision making. In particular, the clinical use of benchmarked values for individual-limb performance on the hop tests may better represent the status of functional performance recovery of the involved limb with the potential to better inform RTS readiness in this vulnerable population.

In this work, our primary objective was to identify age-relevant and activity-relevant single-leg hop test target values from athletes without a history of ACL injury for individual-limb performance and symmetry between limbs, as well as to evaluate the proportion of young athletes post-ACLR at the time of RTS clearance who met the newly derived target values. We hypothesized that a moderate to high proportion of the ACLR group would achieve the newly derived individual-limb performance and symmetry between limbs target values and that a lower proportion of the ACLR group would meet the newly derived symmetry between limbs target values compared with the traditional 90% LSI criterion.

Single-leg hop tests are often used in conjunction with patient-reported outcome measures and assessment of thigh muscle strength to guide rehabilitation decision making, including clearance for sport participation. Several groups[12–14] reported positive associations among knee-related function, quadriceps muscle strength, and functional performance at various time points post-ACLR but also indicated that high-level performance on 1 measure did not reflect similar high-level performance on other measures. In particular, quadriceps femoris strength deficits were often apparent even when performance on functional performance measures, such as single-leg hop tests, was good.[10,15–19] To further understand these associations in the context of the newly derived hop test target values, our secondary objective was to determine clinical measures associated with meeting the new target values at the time of RTS post-ACLR. We hypothesized that better patient-reported function and quadriceps strength in young individuals post-ACLR would be associated with meeting the newly derived target values for hop tests. The determination of age-relevant and activity-relevant normative values, along with additional information about clinical factors associated with achieving the benchmarked values, may provide a more complete picture of limb recovery to inform rehabilitation interventions and progression.

METHODS

Participants

Individuals were included from the larger ACL Reconstruction Long-Term Outcomes in Adolescents and Young Adults (ACL-RELAY) study in this cross-sectional analysis. The ACL-RELAY study is an ongoing, prospective, longitudinal cohort study examining outcomes post-ACLR in young, active individuals and has been previously described.[13–15] Potential participants were recruited from local orthopaedic practices, physical therapy clinics, and the general community surrounding the Cincinnati, Ohio, and northern Kentucky area. Young individuals post-ACLR and those without previous injury (uninjured individuals) were enrolled in the ACL-RELAY study. For this analysis, we included individuals who were 13 to 25 years old. We excluded those who had a modified ACLR procedure due to open epiphyseal plates in the tibia or femur. We also excluded individuals older than 25 years as they tend to have a lower risk of second ACL injury.[5] For the parent study and this analysis, participants with ACLR were required to have completed a formal rehabilitation program and been cleared for return to full sport participation by their orthopaedic surgeon and treating rehabilitation specialist and have a goal of returning to regular engagement ($>$50 hours per year) in a cutting, pivoting, jumping, or lateral-motion sport. For individuals with ACLR, we did not control the rehabilitation program or the decision for RTS clearance. Potential participants with ACLR were excluded if they reported low back pain or lower extremity injury or surgery in either limb (other than the primary ACL injury) that required the care of a physician in the preceding year or sustained a concomitant knee ligament injury ($>$grade 1 medial collateral ligament sprain). Uninjured individuals were enrolled in a control

group and were included if they regularly engaged (>50 hours per year) in a cutting, pivoting, jumping, or lateral motion sport and did not report a history of any major lower limb injury or low back pain in the preceding year that required care from a physician.

Testing Session

We collected the data for this analysis during 1 laboratory testing session. For individuals with ACLR, the testing session occurred within 4 weeks of medical clearance for full sport participation. We collected anthropometric data, including height (cm) and weight (kg), for all participants.

Hop Testing. All participants (ACLR and control groups) completed 4 single-leg hop tests[8] in the following order: single hop for distance (measured in cm), triple hop for distance (cm), crossover hop for distance (cm), and 6-m timed hop (seconds). Each person received oral and visual instructions in the performance of each hop test at the time of data collection. The arms were free to move during testing. Participants performed a practice trial, followed by 2 measurement trials on each limb (randomized limb order). For the distance hop test, we instructed them to hop forward as far as possible while maintaining a controlled landing on the ipsilateral limb. For the 6-m timed hop, we instructed them to hop as quickly as possible, on a single limb, over a 6-m distance. For the distance hop tests, we normalized limb performance values by height. To evaluate symmetry between limbs, the LSI was calculated (LSI = ratio of the involved and uninvolved limb performance × 100%) for each single-leg hop test using the average of 2 measurement trials for each limb. An LSI score of <100% indicated performance deficits in the involved limb. For the control group, we identified the "involved" limb as the lowest performing limb for each hop test. This single-leg hop testing battery is commonly used in the clinical setting and had good reliability (intraclass correlation coefficients = 0.82–0.93) in both individuals post-ACLR and uninjured individuals.[6]

Knee-Related Function. For participants in the ACLR group, self-reported knee function was assessed using the Knee injury and Osteoarthritis Outcome Score (KOOS)[20–22] before hop testing. The KOOS comprises 5 subscales that evaluate different constructs of knee-related function: pain (KOOS-Pain), symptoms (KOOS-Symptoms), activities of daily living (ADL; KOOS-ADL), sports and recreation (KOOS-Sport), and knee-related quality of life (QOL; KOOS-QOL). Each question was marked on a 0 to 4 Likert scale, and scores were converted to a 0 to 100 score (with 100 indicating *no knee problems*) for each subscale (scored independently).[20,21] The KOOS was a valid and reliable measure of knee-related function in athletes post-ACLR.[20–22]

Strength Testing. For individuals in the ACLR group, quadriceps femoris strength was assessed during a maximal volitional isometric contraction (knee flexion = 60°) using an electromechanical dynamometer (Biodex Medical Systems, Inc). Participants were securely positioned with the trunk supported, the hips flexed to approximately 90°, the knee joint aligned with the dynamometer axis, and the dynamometer resistance pad at the anterior aspect of the distal shank, as previously reported.[13,14,23,24] Real-time visual feedback (a bar showing the level of force output) and oral encouragement were provided to encourage maximal-effort trials. After 2 warm-up trials, 3 maximal-effort trials were recorded for each limb (5 seconds in duration, separated by 15 seconds of rest); the uninvolved limb was tested first. Peak torque values from each trial were normalized by body mass (newton meter [Nm]/kg). The average peak torque value of each limb from the test trials was used to calculate an LSI, with values <100% indicating quadriceps femoris strength deficits in the surgical limb.

Statistical and Data Analysis

All statistical analyses were performed using SPSS (version 27; IBM Corp; $\alpha = .050$). Means, standard deviations, and frequencies were calculated to describe sample characteristics. Demographic data were compared between the ACLR and control groups using independent 2-sample *t* tests (continuous data) and Pearson χ^2 tests (categorical data).

Derivation of Single-Leg Hop Test Target Values. Control group single-legged–hop test data were summarized using descriptive statistics. Target values were defined as the lower bound of a 95% CI for each hop test from the control data.[25] Single-leg hop test target values were defined for surgical-limb performance (normalized by height; normalized target values) and for LSI values (LSI target values) for each hop test (Table 1).

Proportion Meeting Target Values. To meet the primary objective of the study, we determined the proportions of the ACLR group who achieved the normalized target values (based on performance of their surgical limb) and LSI target values at the time of testing (within 4 weeks of RTS clearance) for each single-leg hop test and cumulatively for all single-leg hop tests (ie, meeting all normalized target values or meeting all LSI target values). We also determined the proportion of the ACLR group who met the traditional 90% LSI criteria for each hop test and across all hop tests. We used McNemar tests to compare the proportions of the ACLR group who achieved the newly derived LSI target values against the proportions of the ACLR group who met the traditional 90% LSI criteria for each hop test.

Predictors of Meeting Target Values in the ACLR Group. We used separate 2-sample *t* tests (continuous data) or Pearson χ^2 tests (categorical data) to evaluate differences between participants in the ACLR group who met or did not meet all normalized target values and all LSI target values for injury variables (presence of meniscal injury: *yes/no*; time from ACLR to testing: *months*; quadriceps strength variables: *peak torque* [Nm/kg]; quadriceps femoris strength LSI > 90%: *yes/no*) and KOOS subscales. For each comparison (normalized target value groups and LSI target-value groups), variables with a *P* value <.1 were put forth as predictors into logistic regression analyses. To meet our secondary objective, separate multivariate logistic regression analyses were conducted to determine predictors of achieving all normalized target values and all LSI target values. The accepted rule of thumb for sufficient power in logistic regression models was 10 events per predictor variable.[26]

Table 1. Hop Test Data From the Control Group for Normalized Limb and LSI Values

Hop Test	Mean ± SD (95% CI)[b]
Normalized	
Single leg[a]	1.0 ± 0.1 (**1.0,** 1.1)
Triple[a]	2.9 ± 0.4 (**2.8,** 3.1)
Crossover[a]	2.7 ± 0.5 (**2.6,** 2.8)
6-m Timed, s	1.9 ± 0.3 (**1.8,** 2.0)
Hop Limb Symmetry Index, %	
Single leg	96.5 ± 0.3 (**96,** 97)
Triple	96.8 ± 0.2 (**96,** 98)
Crossover	96.5 ± 0.3 (**96,** 97)
6-m Timed	95.6 ± 0.5 (**94,** 97)

[a] Hop distance relative to participant height.
[b] Hop test target values defined as the lower bound of 95% CI for each hop test for the "involved" limb (worse-performing limb) performance (normalized) and symmetry between limbs (Limb Symmetry Index). Bold indicates hop test target value.

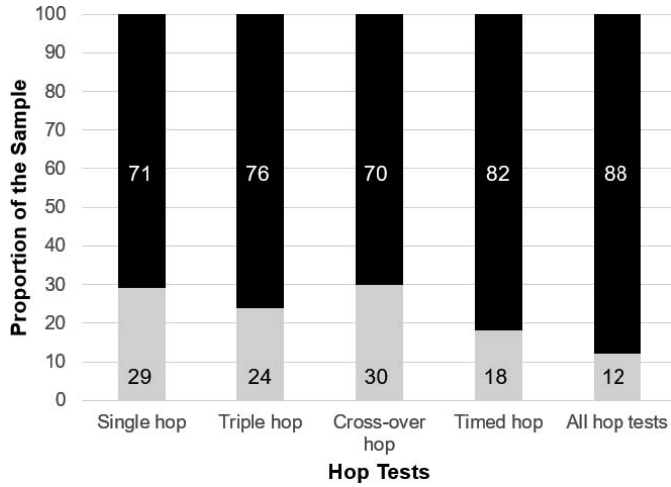

Figure 1. Proportions of participants in the ACLR group meeting normalized target values (Table 1) with their surgical limb for each single-leg hop test and across all single-leg hop tests; gray = met normalized target values, black = did not meet normalized target values. Abbreviations: ACLR, anterior cruciate ligament reconstruction; All, met target values for all hop tests; CH, crossover hop for distance; SH, single hop for distance; TiH, 6-m timed hop; TrH, triple hop for distance.

RESULTS

Demographic Data

The ACLR group (n = 159) and control group (n = 47) did not differ in age, sex distribution, height, or distribution of level of sport participation (Table 2). The weight of the ACLR group was higher than that of the control group (P = .019; Table 2).

Proportions of the ACLR Group Meeting Single-Leg Hop Target Values

Target values, derived from the control group data, were calculated for normalized target values and LSI target values for each single-leg hop test (Table 1). Low proportions of the ACLR group (18%–30%) met the normalized target values with their surgical limb on individual hop tests, and only 12% of the ACLR group met the normalized target values for all hop tests (Figure 1). For symmetry between limbs, moderate proportions of the ACLR group (43%–69%) met the LSI target values on individual hop tests and a small proportion of the ACLR group (25%) met the LSI target values for all hop tests (Figure 2). The proportion of the ACLR group that achieved the newly derived LSI target values was lower than the proportion of the ACLR group that achieved the traditional 90% LSI values on all hop tests (single hop = 43% versus 79%, respectively; triple hop = 48% versus 82%, respectively; crossover hop = 50% versus 79%, respectively; timed hop = 69% versus 84%, respectively; all hops = 25% versus 60%, respectively; all P values < .001).

Table 2. Demographic Data for the Cohort[a]

Variable	Group		P Value
	Anterior Cruciate Ligament Reconstruction Group (n = 159)	Control (n = 47)	
Age, y	16.9 ± 2.2 (range = 13–25)	17.0 ± 2.3 (range = 14–23)	.810
Sex, % females	72	68	.572
Height, cm	168.3 ± 9.2	167.5 ± 9.3	.613
Mass, kg	68.0 ± 14.30	62.5 ± 12.6	.019[b]
Level of sport participation, %			.692
Collegiate/high school competitive[c]	84[d]	79	
Competitive[e] and recreational or club[c]	14[d]	17	
Recreational or club[e]	2[d]	4	
Graft type distribution, %			
Patellar tendon-bone autograft	37	NA	NA
Hamstrings autograft	56	NA	NA
Allograft	7	NA	NA
Meniscal injury, %	48	NA	NA
Time from surgery to testing, mo	8.5 ± 2.9	NA	NA

Abbreviation: NA, not applicable.
[a] Data are reported as mean ± SD or proportion (%) of the group.
[b] Indicates P < .05.
[c] Sports such as basketball, football, rugby, and soccer.
[d] Preinjury.
[e] Sports such as baseball, softball, and tennis.

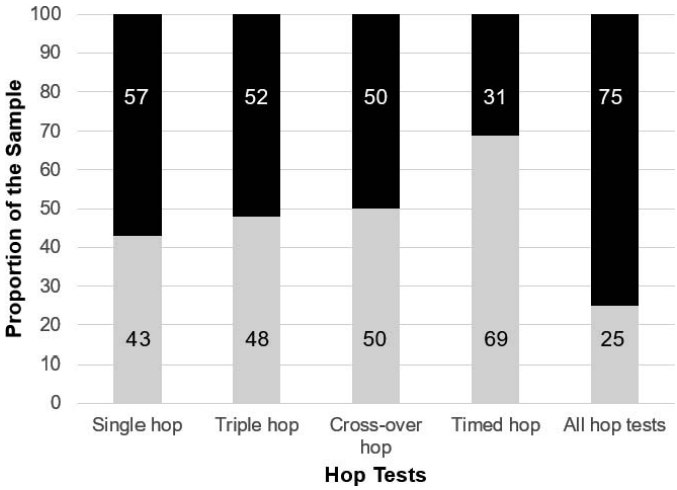

Figure 2. Proportions of participants in the ACLR group meeting LSI target values (Table 1) for each single-leg hop test and across all single-leg hop tests; gray = met LSI target values, black = did not meet LSI target values. Abbreviations: ACLR, anterior cruciate ligament reconstruction; All, met target values for all hop tests; CH, crossover hop for distance; LSI, limb symmetry index; SH, single hop for distance; TiH, 6-m timed hop; TrH, triple hop for distance.

Predictors of Meeting All Single-Leg Hop Tests Normalized or LSI Target Values

In the ACLR group, injury, quadriceps strength, and KOOS data for the group that attained all normalized target values (n = 19) and the group that did not attain all normalized target values (n = 140) are shown in Table 3. The group that met all normalized target values had a higher normalized surgical-limb quadriceps peak torque compared with the group that did not meet all normalized target values (Table 3). Predictors for the logistic regression analysis included surgical-limb and uninvolved-limb normalized quadriceps femoris peak torque to predict achievement of all normalized hop test target values. From the logistic regression analyses, we found that higher surgical-limb normalized quadriceps femoris peak torque was associated with greater odds of meeting all normalized target values. Specifically, for every 1 Nm/kg increase in quadriceps peak torque in the involved limb, the odds of meeting all normalized target values were approximately 4.1 times greater (odds ratio = 4.10 [1.10, 15.24], $P = .035$).

In the ACLR group, injury, knee-related function, and quadriceps strength data for the group that met all LSI target values (n = 40) and the group that did not meet all LSI target values (n = 119) are shown in Table 4. The group that achieved all LSI target values demonstrated higher (better) KOOS-Pain, Symptoms, Sports, and QOL subscale scores, as well as a higher surgical-limb normalized quadriceps peak torque and a greater proportion with quadriceps femoris LSI $\geq$ 90% than those who did not attain all LSI target values (Table 4). Potential predictors of meeting all LSI target values in the logistic regression analysis, including KOOS-Pain, Symptoms, Sports, and QOL subscale scores; surgical-limb normalized quadriceps peak torque; and having quadriceps femoris strength LSI $\geq$ 90% (*yes/no*), were entered into the model. From the logistic regression analyses, we observed a trend that those who had quadriceps femoris strength LSI $\geq$ 90% had approximately 2.4 times greater odds of meeting all LSI target values (odds ratio = 2.44 [0.97, 6.14]; $P = .058$).

DISCUSSION

Our primary objective in this study was to identify age-relevant and activity-relevant single-leg hop test target values in athletes without a history of ACL injury for individual-limb performance and between-limbs symmetry, as well as to evaluate the proportion of young athletes post-ACLR who met the newly derived target values at the time of RTS clearance. The most important findings were that the newly derived normalized hop test target values and LSI hop test target values were more stringent than those commonly used to inform RTS clearance and that few young athletes post-ACLR met or exceeded these target values at the time of RTS clearance. For individual single-leg hop tests, only 18% to 30% of young athletes at the time of RTS clearance post-ACLR achieved the target values for surgical-limb performance (normalized target values). Further, only 12% met the normalized target values for all 4 hop tests. Hop test performance is often evaluated

Table 3. Variables of Interest for Those Post-Anterior Cruciate Ligament Reconstruction Who Met and Those Who Did Not Meet All Normalized Target Values[a]

Variable	Normalized Target Values		*P* Value
	Met All (n = 19)	Did Not Meet All (n = 140)	
Meniscal injury as proportion of group, %	53	47	.653
Time from surgery to testing, mo	8.4 ± 2.7	8.5 ± 3.0	.853
Knee injury and Osteoarthritis Outcome Score			
Pain	95.1 ± 5.5	92.6 ± 8.6	.218
Symptoms	86.4 ± 10.2	85.9 ± 13.4	.874
Activities of Daily Living	98.3 ± 2.4	97.2 ± 5.8	.443
Sport and Recreation	90.0 ± 10.0	85.9 ± 14.8	.249
Quality of Life	73.1 ± 21.4	72.4 ± 18.7	.883
Quadriceps femoris peak torque, Nm/kg			
Surgical limb	2.7 ± 0.4	2.3 ± 0.5	.006[b]
Uninvolved limb	2.8 ± 0.5	2.6 ± 0.5	.089
Quadriceps femoris Limb Symmetry Index $\geq$ 90% as proportion of group, %	63	55	.501

[a] Data are reported as mean ± SD unless otherwise noted.
[b] Indicates $P < .05$.

Table 4. Variables of Interest for Those Post-Anterior Cruciate Ligament Reconstruction Who Met and Those Who Did Not Meet All LSI Target Values[a]

Variable	LSI Target Values		*P* Value
	Met All (n = 40)	Did Not Meet All (n = 119)	
Meniscal injury as proportion of group, %	38	51	.132
Time from surgery to testing, mo	8.3 ± 2.4	8.6 ± 3.1	.356
Knee injury and Osteoarthritis Score scale			
Pain	95.5 ± 5.6	92.0 ± 8.7	.020[b]
Symptoms	90.2 ± 10.9	84.6 ± 13.1	.017[b]
Activities of Daily Living	98.5 ± 3.5	97.0 ± 6.0	.145
Sport and Recreation	90.8 ± 14.5	85.0 ± 14.1	.027[b]
Quality of Life	80.9 ± 19.2	70.9 ± 18.1	.037[b]
Quadriceps femoris peak torque, Nm/kg			
Surgical limb	2.5 ± 0.4	2.3 ± 0.5	.026[b]
Uninvolved limb	2.6 ± 0.6	2.6 ± 0.4	.877
Quadriceps femoris LSI ≥ 90% as proportion of group, %	75	50	.005[b]

Abbreviation: LSI, limb symmetry index.

[a] Data are reported as mean ± DS unless otherwise noted.

[b] Indicates $P < 0.05$.

using an LSI to assess performance symmetry between limbs with recommendations for RTS clearance of LSI > 90%.[6–8] All of the newly derived age-relevant and activity-relevant hop test target values for symmetry (LSI target values) were >90% (94%–96%). On individual single-leg hop tests, 43% to 69% of young athletes attained the LSI target values at the time of RTS clearance post-ACLR, but only 25% attained the LSI target values on all hop tests. In line with our hypothesis, a smaller proportion of the ACLR group achieved the newly derived LSI target values compared with the traditional LSI > 90% criterion for all hop tests.

Our secondary objective was to determine clinical measures associated with meeting the newly derived target values post-ACLR. Our hypothesis was partially supported in that a higher surgical-limb quadriceps femoris peak torque at the time of RTS was associated with meeting all normalized target values in the surgical limb. Benchmarking the hop test performance of young athletes post-ACLR against these newly derived age-relevant and activity-relevant normative surgical-limb performance values, obtained from an uninjured control group, may better represent the status of functional performance recovery in the surgical limb with the potential to better inform RTS readiness in this young, active patient population.

Functional performance measures are often used clinically to track rehabilitation progress and inform readiness for RTS post-ACLR.[10,27–29] Clinical milestones related to functional performance are frequently evaluated with a battery of single-leg hop tests, with symmetry between limbs in hop test performance (LSI value) commonly reported as the criterion to "pass" in order to return to sport participation (LSI > 90%).[6–8] Measuring hop test performance with LSI values is a practical clinical strategy; however, the authors[9] of a recent systematic review reported only a fair positive association between hop test performance (LSI > 90%) and successful RTS participation (at 12 months). Several sets of researchers[10,30–32] studies characterized further shortcomings of the current single-leg hop LSI recommendations, including the use of the uninvolved limb as the reference standard, which may have led to an overestimation of involved limb functional performance post-ACLR and erroneous interpretation. Indeed, among young individuals post-ACLR, a high level of symmetry between limbs in movement patterns or functional performance was often attained by reduced loading or performance, respectively, of the uninvolved limb.[10,31] In our analysis, 79% to 84% of the ACLR group met the traditional 90% LSI values on the individual hop tests, while only 43% to 69% met the newly derived hop test LSI target values (target values of 94% to 96%). This demonstrates that the traditional 90% criterion for performance symmetry between limbs during functional performance is likely too low; however, using the LSI target values alone does not address the potential shortcomings of using measures of symmetry to evaluate functional performance. As such, we derived age-relevant and activity-relevant normalized-limb performance target values (normalized target values) for the surgical limb.

Only 18% to 30% of the ACLR group was able to meet the normalized limb performance target values for the surgical limb, indicating that a majority of this ACLR cohort, who were cleared for sport participation, lacked the functional performance capacity of their age-similar and activity-similar peers. Recent work[33] in young uninjured athletes (age = 6–18 years old) provided normative values for many common functional performance tests, including some of the single-leg hop tests we used (single hop, crossover hop, 6-m timed hop). The average age of participants in their study (11.7 years)[33] was younger than that of our uninjured cohort (17.0 years). Although height was a significant predictor of all performances on the hop tests, their results were reported as raw values (cm and seconds),[33] limiting direct comparison with our normalized data. Differences in age between the cohorts (current analysis = 17.0 ± 2.3 years versus previous study = 11.7 ± 3.6 years [33]) and height (current analysis = 167.5 ± 9.3 cm versus previous study = 59.3 ± 8.1cm[33]) likely explained the higher raw values in our uninjured group compared with those of Magill et al[33] (single hop = 169.8 ± 24.1 cm versus 102.1 ± 29.9 cm, crossover hop = 454.2 ± 86.2 cm versus 287.9 ± 106.2 cm, 6-m timed hop = 1.9 ± 0.3 seconds versus 2.7 ± 0.8 seconds, respectively). The normalized target values reported in our study represented

activity-relevant normalized (by height) limb performance values for adolescents and young adults who regularly participated in cutting and pivoting sports.

We noted that a higher involved-limb quadriceps femoris peak torque and quadriceps femoris strength LSI $>$ 90% showed a trend toward being factors associated with meeting the newly derived normalized and LSI hop test target values, respectively. Surgical-limb quadriceps femoris strength was lower in the groups that did not achieve the normalized or LSI hop test target values compared with the groups that achieved the normalized or LSI hop test target values. Quadriceps femoris strength deficits remain a ubiquitous impairment throughout the rehabilitation plan of care post-ACLR.[13,14,23,34–36] These deficits also persisted after rehabilitation, with a substantial portion of young athletes demonstrating quadriceps strength deficits at the time of medical clearance for sports participation[15,24,35] and beyond.[13,23,34] Our findings were consistent with previous work showing that quadriceps strength deficits contributed to worse functional performance[13,34,35] and altered movement patterns.[14,23,34,35] Optimizing involved limb quadriceps femoris strength and performance may be an important rehabilitation target throughout the plan of care to maximize the odds of attaining age-relevant and activity-relevant functional performance benchmarks in the surgical limb in preparation for RTS participation.

We evaluated athletes who were within 4 weeks of medical clearance for full sport participation. We did not control the rehabilitation program or the decision for release to RTS. Many investigators have recommended RTS criteria of LSI values $\geq$ 90% for quadriceps strength and functional performance measures, as well as a high score (eg, 90/100) on patient-reported measures of function. However, a substantial portion of this cohort displayed values lower than those currently recommended, as has been previously shown.[15] This result continues to highlight the need for objective measures to inform readiness for sport participation or continued interventions. For evaluation of strength and functional performance, using age-relevant and activity-relevant values for benchmarking limb performance, rather than LSI, may better inform the determination of RTS readiness of young individuals post-ACLR, although further examination is needed. Unknown is whether these benchmarks would predict second ACL injury, which was beyond the scope of this study. This study filled a critical gap in the literature by establishing identifying age-relevant and activity-relevant normative data for single-leg hop tests, a common assessment of functional performance used for RTS decision making post-ACLR.

Limitations

Several limitations of our investigation should be acknowledged. First, the age-relevant and activity-relevant hop test target values applied only to active adolescents and young adults post-ACLR, given the characteristics of the uninjured population from whom these target values were derived. Second, the hop test target values were derived across both sexes, although sex-specific target values may be warranted for some functional performance measures.[33] Although the distribution of sexes between our control and ACLR cohorts was similar, females dominated (68% and 72%, respectively), warranting further work to determine sex-specific hop test target values. Third, we did not evaluate limb preference, which may have affected the results of the ACLR group. Fourth, we examined only factors associated with meeting all normalized or all LSI hop test target values, not the target values for each individual hop test. This is consistent with the clinical use of a battery of hop tests (rather than a single test) to evaluate functional performance. Finally, we did not evaluate the effect of meeting the age-relevant and activity-relevant hop test target values on longitudinal outcomes, which remains an area of ongoing analysis in this cohort.

CONCLUSIONS

Age-relevant and activity-relevant hop test target values, derived from young and active uninjured individuals, were more stringent than those used traditionally to inform RTS decisions post-ACLR (ie, LSI $\geq$ 90%).[6–8] Factors associated with meeting the age-relevant and activity-relevant hop test target values included greater normalized surgical-limb quadriceps femoris strength and a quadriceps femoris strength LSI $\geq$ 90%. Only a small to moderate proportion of young, active individuals post-ACLR at the time of RTS clearance met the age-relevant and activity-relevant hop test target values, which is considerably lower than the proportion who meet the traditional criterion of LSI $\geq$ 90%. The possible shortcomings of symmetry between limbs data in evaluating the functional capacity of the involved limb create the opportunity to benchmark hop test performance against these newly derived age-relevant and activity-relevant normative values to potentially better inform the determination of RTS readiness in this young patient population.

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