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Thigh-Muscle and Patient-Reported Function Early After Anterior Cruciate Ligament Reconstruction: Clinical Cutoffs Unique to Graft Type and Age

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Context: Patient-reported function is an important outcome in anterior cruciate ligament rehabilitation. Identifying which metrics of thigh-muscle function are indicators of normal patient-reported function can help guide treatment.

Objective: To identify which metrics of thigh-muscle function discriminate between patients who meet and patients who fail to meet age- and sex-matched normative values for patient-reported knee function in the first 9 months after anterior cruciate ligament reconstruction (ACLR) and establish cutoffs for these metrics by covariate subgroups.

Design: Cross-sectional retrospective study.

Setting: Laboratory.

Patients or Other Participants: A total of 256 patients (129 females, 128 males; age = 17.1 ± 3.0 years, height = 1.7 ± 0.1 m, mass = 74.1 ± 17.9 kg, months since surgery = 6.4 ± 1.4), 3 to 9 months after primary unilateral ACLR.

Main Outcome Measure(s): We stratified the sample into dichotomous groups by the International Knee Documentation Committee (IKDC) score ($IKDC_{MET}$, $IKDC_{NOT\ MET}$) using sex- and age-matched normative values. We measured quadriceps and hamstrings isokinetic (60°/s) torque and power bilaterally. Normalized quadriceps and hamstrings peak torque (Nm/kg) and power (W/kg), limb symmetry indices (LSI, %), and hamstrings : quadriceps ratios were calculated. Logistic regression indicated which of these metrics could predict IKDC classification while controlling for age, graft type, and sex. Receiver operating characteristic curves established cutoffs for explanatory variables for both total cohort and covariate subgroups. Odds ratios (OR) determined the utility of each cutoff to discriminate IKDC status.

Results: Quadriceps torque LSI (≥69.4%, OR = 3.6), hamstrings torque (≥1.11 Nm/kg, OR = 2.1), and quadriceps power LSI (≥71.4%, OR = 2.0) discriminated between IKDC classification in the total cohort. Quadriceps torque LSI discriminated between IKDC classification in the patellar-tendon graft (≥61.6%, OR = 5.3), hamstrings-tendon graft (≥71.8%, OR = 10.5), and age <18 years (≥74.3%, OR = 5.2) subgroups. Hamstrings torque discriminated between IKDC classifications in the age <18 years (≥1.10 Nm/kg, OR = 2.6) subgroup.

Conclusions: Quadriceps torque LSI, hamstrings torque, and quadriceps power LSI were the most useful metrics for predicting normal patient-reported knee function early after ACLR. Further, cutoff values that best predicted normal patient-reported function differed by graft type and age.

Key Words: IKDC, patient-reported outcomes, quadriceps strength, hamstrings strength

Key Points

- Quadriceps strength limb symmetry index was the best predictor of individuals who met sex- and age-specific patient-reported outcomes after anterior cruciate ligament reconstruction.
- Hamstrings strength was the second-best predictor of patient-reported function.
- Clinically meaningful cutoffs of thigh-muscle strength metrics that explained sex- and age-specific patient-reported outcomes were different in graft type and age subgroups.

Patient-centered medicine as part of a high-value health care system challenges clinicians to place patient goals and patient-reported function first by targeting modifiable impairments that are most likely to optimize both short- and long-term function.[1,2] Patient-reported function has been increasingly used in determining readiness to return to activity[3] and overall success of the course of treatment.[4] Despite this, Burgi et al[5] in a recent review showed that in 42% of studies, time since surgery was the sole criterion used to determine readiness for return to activity after anterior cruciate ligament reconstruction (ACLR).[5–7] This requires clinicians to prepare patients for a lifetime of successful knee function in as little as 3 to 9 months postoperatively. Persistent reductions in patient-reported knee function using the International Knee Documentation Committee (IKDC) Subjective Knee Evaluation, a staple for subjective knee function assessment in active populations, are common in individuals post-ACLR and parallel chronic limitations in function.[8,9] Therefore, knowing which clinical impairments and metrics of clinical assessment predict normal patient-reported knee function in the early postoperative period will help clinicians prioritize highly effective treatment.[8]

After ACLR, the recommendation based on best evidence is a multimodal assessment of thigh-muscle function (eg, isokinetic and isometric strength testing), commonly evaluated as quadriceps and hamstrings peak torque and average power, for tracking both patient recovery and readiness to return to activity.[10] Each metric can then be normalized to (1) body mass (Nm/kg, W/kg), (2) the contralateral limb (limb symmetry index [LSI]), or (3) the antagonist muscle group (hamstrings:quadriceps [H:Q] ratio). These expressions of thigh-muscle function provide useful impairment-level data and have been associated with functional outcomes such as landing mechanics, hop-test performance, and return-to-play success.[11–13] However, each has its own limitations, and which is the best indicator of patient-reported knee function is unclear. For example, quadriceps strength symmetry is commonly quantified; however, this may be confounded by bilateral alterations in quadriceps strength after joint injury and is reported to overestimate function.[7] Overestimation of strength could minimize the need to continue treatment and promote return to activity without sufficient muscle recovery. This has sparked a debate concerning what constitutes sufficient strength and the relative importance of strength symmetry. Considering the multidirectional demands of sports and exercise, it is important to consider metrics beyond peak torque as traditionally described.[14] *Muscle power*, the product of force and velocity, measures the ability to generate a high level of force quickly, which is important for both performance and injury prevention.[14] Decreased muscle power is associated with both muscle atrophy and fiber type,[15] which are known to change after ACLR.[16] Further, 84% of patients expect to return to sport by 12 months postoperatively[17] despite persistent deficits in quadriceps muscle power.[8,9,18]

Greater quadriceps power has been associated with better patient-reported knee function within 2 years of ACLR.[8,9] Other scientists continue to raise questions regarding the utility of hamstrings strength[19] and the value of intralimb strength assessment (H:Q ratio)[20] for predicting patient-reported function. The hamstrings muscles are anatomical anterior cruciate ligament agonists and dynamic stabilizers of the knee against anterior tibial translation. Impairments in hamstrings strength are linked to injury risk,[20] and differences exist between limbs after ACLR.[21] Interestingly, little is known about the hamstrings relative to patient-reported knee function, despite impairments in strength, volume, and atrophy during this postoperative period,[19] suggesting this is an important relationship to investigate. Because the breadth of data available to clinicians on thigh strength assessment is overwhelming, establishing a connection between those metrics most related to health-related outcomes may help guide treatment decision making.

To this end, recent evidence has emerged regarding the ability of both unilateral quadriceps strength and LSI cutoff scores to predict patient-reported knee function using the IKDC.[13,22,23] Although clinically meaningful cutoff scores are useful, past work had several limitations. Namely, it is well accepted that sex, graft type, age, and time from surgery influence thigh strength[24] and should be appropriately considered before determining cutoffs; however, previous work has not completely included these. Furthermore, IKDC normative values are influenced by sex and age.[25] Additional limitations include the use of IKDC cutoffs established for heterogenous cohorts that do not consider differences in these factors. Using IKDC benchmarks of satisfactory (76%)[23] or arbitrary (90%)[13,22] scores may fail to appropriately control for confounding factors (namely, age and sex) in assessing normal knee function during the early postoperative period. Our contention is that published age- and sex-matched IKDC normative values provide better control of these patient-specific factors when one is interpreting the level of function. Lastly, to our knowledge, the relationships between other common metrics of thigh-muscle function (eg, hamstrings torque, power, or H:Q ratio) and patient-reported knee function have not been investigated. Therefore, the purpose of our analysis was to identify which metrics of thigh-muscle function were able to discriminate between patients who met and patients who failed to meet age- and sex-matched IKDC normative values in the first 9 months after ACLR. We hypothesized that greater involved-limb and more symmetric quadriceps and hamstrings muscle function (ie, strength and power) and a higher H:Q ratio could discriminate between patients who met and those who failed to meet age- and sex-matched normative IKDC values. The secondary purposes were to establish cutoff values for those metrics able to discriminate, including cutoffs specific to graft-type and age subgroups, and determine the ability of each to predict IKDC classification. We hypothesized that cutoffs would differ by graft-type and age subgrouping and that each would demonstrate metrics that could predict the ability to meet normative IKDC values.

METHODS

This was a cross-sectional retrospective analysis in which we sought to define the most useful metrics of thigh-muscle function for discriminating between patients who met and those who failed to meet age- and sex-appropriate normative IKDC scores within the early (<9 months) postoperative period. Included explanatory variables were involved-limb quadriceps and hamstrings isokinetic strength and power, expressed as mass-normalized unilateral metrics, LSIs, and H:Q ratios. The dependent variable was IKDC score.

Participants

Data were compiled from 3 unique sites with common isokinetic protocols that were originally collected as parts of larger individual studies. Institutional review board approval was obtained at all 3 sites. Data from 400 unique participants were considered for inclusion in this study. Participants who were status post primary unilateral ACLR with patellar-tendon (PT) or hamstrings-tendon (HT) autograft, were between the ages of 15 and 34 years old, and had completed the IKDC and the isokinetic assessment protocol of the quadriceps and hamstrings were included. Volunteers with a contralateral limb injury, multiligament reconstruction, revision ACLR, or any other subsequent procedure (eg, manipulation under anesthesia) before data collection were excluded. Given that the purpose of our study was to identify clinically meaningful impairments that could be targeted during a period of ongoing rehabilitation and before the return to sport, participants who were >9 months or <3 months postoperative were excluded. Of the 400 potential participants, 257 were included in this study based on the described criteria.

Procedures

Each of the research sites used similar procedures for the assessment of lower extremity strength after ACLR, including (1) assessment of patient-reported knee function using the IKDC and (2) assessment of thigh-muscle strength using isokinetic dynamometry. Participants completed the IKDC, which is a valid assessment of patient-reported knee function related to health-related quality of life, for quantification of patient-reported knee function before strength testing.[25] They performed isokinetic strength and power testing of the quadriceps and hamstrings using an isokinetic dynamometer (Biodex Systems Inc, Shirley, NY). All participants were positioned seated with their hips flexed to 85° and knees initially flexed to 90° and immobilized using straps, and a limb-weight correction was used. During testing, they were asked to sit upright with the head and shoulders against the chair and arms crossed. They were instructed to kick and pull as hard and fast as possible, giving maximal effort, and were allowed to practice until comfortable with the test. The examiners provided maximal oral encouragement throughout testing. Isokinetic quadriceps and hamstrings strength was measured during 5 consecutive concentric contractions at 60°/s. The uninvolved limb was tested before the involved limb.

Data Analysis

Patient-Reported Knee Function. Based on previously established normative values for the IKDC,[25] we used the 15th percentile of the participant-specific age- and sex-matched normative value for each participant.[26] According to the current literature, this cutoff appears appropriate considering that our sample would not be expected to return to normal patient-reported function during the subacute postoperative window evaluated. Any participant under the age of 18 years was placed in the 18- to 24-year normative range for his or her sex, as previously described,[26] and the sample was then divided into dichotomous groups ($IKDC_{MET}$, $IKDC_{NOT\ MET}$). The IKDC values for each age and sex group were as follows: females: <18 years = 83.9 (n = 95), 18 to 24 years = 83.9 (n = 28), and 25 to 34 years = 82.8 (n = 6); males: <18 years = 89.7 (n = 91), 18 to 24 years = 89.7 (n = 33), and 25 to 34 years = 86.2 (n = 3).

Muscle Function. Peak torque (Nm/kg) and average power (W/kg) for the quadriceps and hamstrings were normalized to body mass. Limb symmetry indices were calculated for both quadriceps and hamstrings torque and power by expressing the involved limb relative to the uninvolved limb as previously described (Equation 1).

$$\text{LSI} = \frac{\text{Involved Limb}}{\text{Uninvolved Limb}} \times 100 \qquad (1)$$

The H:Q ratio represents the strength ratio between the peak torque or power values of the involved limb. The ratio was calculated by expressing hamstrings torque or power relative to quadriceps torque or power as previously described (Equation 2).

$$\text{H:Q Ratio} = \frac{\text{Hamstrings Torque or Power}}{\text{Quadricepes Torque or Power}} \qquad (2)$$

Statistical Analysis

Data were assessed for normality as indicated by skewness and kurtosis. Descriptive statistics were calculated for patient demographics and outcome measures. We then determined which explanatory variables would be appropriate to include in our analysis by conducting separate independent *t* tests to determine if outcomes differed between the $IKDC_{MET}$ and $IKDC_{NOT\ MET}$ classifications. Variables that differed were considered for further analysis.

In the second step of our analysis, we performed binomial logistic regression with forward selection (likelihood ratio) to determine which explanatory variables were able to predict IKDC status while controlling for sex, graft type, age, and time from surgery. The covariates were first entered into the model as block 1 (enter), followed by the explanatory variables as block 2 (forward entry) to determine the model characteristics of the strength data in isolation. For 179 participants (70%), power data were not available. Given the unequal sample sizes, separate models were constructed for the torque and power data.

In the third step of our analysis, we constructed separate receiver operating characteristic (ROC) curves to determine the individual capacity of each variable that significantly contributed to our logistic regression models to discriminate between IKDC classifications. Subgroups were created if the covariate was significant in the regression model. The area under the curve (AUC) and corresponding 95% confidence intervals were used to determine the accuracy of all explanatory variables in discriminating the IKDC classification. The strength of the AUC was interpreted as *excellent* (0.9–1.0), *good* (0.8–0.9), *fair* (0.7–0.8), or *poor* (0.5–0.7).[27] Receiver operating characteristic curves were then inspected with the Youden method to identify cutoff values of significant explanatory variables that maximized sensitivity (Sn) and specificity (Sp).[28] Cutoff values, AUC, Sn, Sp, and positive and negative likelihood ratios (+LR and –LR) were calculated for each variable.

In the final step of our analysis, we constructed χ^2 contingency tables to determine the odds of meeting normative IKDC values when achieving the identified cutoff values for the total cohort and subgroups. The level of statistical significance was set a priori at $P \leq .05$. All statistical analyses were performed using SPSS (version 25.0; IBM Corp, Armonk, NY).

RESULTS

Demographics

Sample demographics and outcome measures are presented in Table 1. All data were normally distributed, except for age, mass, and H:Q ratios. Group allocation by IKDC classification resulted in 146 participants (56.8%) who met the criteria.[26]

Table 1. Demographic Characteristics

Characteristic	International Knee Documentation Committee Subjective Knee Evaluation Form Score				
	Met		Not Met		
	n (%)	n	n (%)	n	*P* Value
Sex, females/males	78 (53.4)/68 (46.6)	146	51 (45.9)/60 (54.1)	111	.258
Graft, patellar tendon/hamstrings tendon	115 (78.8)/31 (21.2)	146	76 (68.5)/35 (31.5)	111	.083
	Mean ± SD	n	Mean ± SD	n	*P* Value
Age, y[a]	17.3 ± 3.0	146	18.0 ± 5.0	111	**<.001**[b]
Height, cm	172.7 ± 10.9	146	174.3 ± 9.3	111	.201
Mass, kg[a]	69.6 ± 24.1	146	74.7 ± 23.1	111	**.026**
Time postsurgery, mo	6.6 ± 1.1	146	6.1 ± 1.6	111	**.009**
International Knee Documentation Committee Form Score, %	94.1 ± 4.3	146	74.9 ± 9.3	111	**<.001**
Quadriceps					
Peak torque (involved limb), Nm/kg	1.70 ± 0.54	146	1.47 ± 0.49	111	**<.001**
Peak torque LSI	0.75 ± 0.16	146	0.64 ± 0.17	111	**<.001**
Average power (involved limb), W/kg	1.31 ± 0.38	28	1.11 ± 0.42	49	**.039**
Average power LSI	0.87 ± 0.14	28	0.72 ± 0.22	49	**<.001**
Hamstrings					
Peak torque (involved limb), Nm/kg	1.05 ± 0.31	146	0.96 ± 0.26	111	**.016**
Peak torque LSI	0.93 ± 0.17	146	0.87 ± 0.18	111	**.004**
Average power (involved limb), W/kg	0.74 ± 0.26	28	0.65 ± 0.22	49	.110
Average power LSI	0.87 ± 0.15	28	0.80 ± 0.21	49	.105
Hamstrings:quadriceps ratio (involved limb)[a]					
Peak torque	0.51 ± 0.22	146	0.61 ± 0.29	111	**.027**
Average power	0.54 ± 0.24	28	0.59 ± 0.22	49	.325

Abbreviation: LSI, limb symmetry index.

[a] Nonnormally distributed data compared with the Mann-Whitney *U* test, median, and interquartile range reported.
[b] Bold indicates a statistically significant value as determined by $P < .05$.

Determination of Useful Thigh Metrics and Subgroups

The results of the logistic regression analyses for peak torque and power metrics are presented in Tables 2 and 3, respectively. Quadriceps peak torque LSI and hamstrings peak torque were significant predictors of IKDC classification.

For the torque metrics, quadriceps peak torque LSI had the largest effect on IKDC classification (β = 4.65, odds ratio [OR] = 104.51 [12.57, 869.17]). Hamstrings peak torque had the second largest effect on IKDC classification (β = 1.10, OR = 3.00 [1.07, 8.36]). Achieving the cutoff values for torque metrics improved the accuracy of classification from 69.1% to 70.3%, meaning a 1.2% improvement over the covariates alone (sex, graft type, age, and time from surgery). Graft type (β = –0.97, OR = 0.38 [0.19, 0.91]) and age (β = –0.22, OR = 0.80 [0.70, 0.91]) were significant covariates. These variables were further analyzed for the total cohort and separately for the graft-type (PT and HT) and age (<18 years and >18 years) subgroups.

Table 2. Logistic Regression Results for the Torque Variables

	Variable Characteristics			Model Characteristics		
	B	*P* Value	Odds Ratio (95% Confidence Interval)	Accuracy, % Correct	Explained Variance, R^2	*P* Value
Block 0: no variables				57.0		
Block 1: covariates (enter)				69.1	0.150	<.001
Sex[a]	−0.160	.555	0.852 (0.50, 1.45)			
Graft type[a]	–0.404	.189	0.667 (0.37, 1.22)			
Age	–0.221	<.001	0.801 (0.72, 0.90)			
Time from surgery	0.258	.009	1.29 (1.07, 1.57)			
Block 2: covariates (enter) + predictors (forward: likelihood ratio)				70.3	0.290	<.001
Sex[a]	–0.312	.294	0.73 (0.41, 1.31)			
Graft type[a]	–0.966	.006	0.38 (0.19, 0.91)			
Age	–0.221	.001	0.80 (0.70, 0.91)			
Time from surgery	0.141	.191	1.15 (0.93, 1.42)			
Quadriceps peak torque limb symmetry index	4.649	<.001	104.51 (12.5, 869.17)			
Hamstrings peak torque	1.097	.036	3.00 (1.07, 8.36)			

[a] Female and patellar-tendon graft used as reference categories. Positive B values indicate that male or hamstrings-tendon graft (or both) displayed higher odds of meeting normal International Knee Documentation Committee Subjective Knee Evaluation Form values.

Table 3. Logistic Regression Results for Power Variables

	Variable Characteristics			Model Characteristics		
	B	P Value	Odds Ratio (95% Confidence Interval)	Accuracy, % Correct	Explained Variance, R^2	P Value
Block 0: no variables				63.6		
Block 1: covariates (enter)				67.5	.200	.016
Sex[a]	–0.426	.419	0.65 (0.23, 1.83)			
Graft type[a]	0.844	.168	2.33 (0.70, 7.72)			
Age	–0.186	.034	0.83 (0.70, 0.99)			
Time from surgery	–0.231	.252	0.79 (0.53, 1.18)			
Block 2: covariates (enter) + predictors (forward: LR)				68.8	.268	.005
Sex[a]	–0.371	.498	0.69 (0.24, 2.01)			
Graft type[a]	0.166	.811	1.18 (0.30, 4.41)			
Age	–0.168	.074	0.85 (0.70, 1.02)			
Time from surgery	–0.227	.278	0.80 (0.53, 1.20)			
Quadriceps power limb symmetry index	3.612	.044	37.04 (1.10, 1253.23)			

[a] Female and patellar-tendon graft used as reference categories. Positive B values indicate that male or hamstrings-tendon graft (or both) displayed higher odds of meeting normal IKDC (International Knee Documentation Committee Subjective Knee Evaluation Form) values.

For the power metrics, quadriceps power LSI was a significant predictor of IKDC classification with no significant covariates. Quadriceps power LSI had the largest effect on IKDC classification ($\beta = 3.61$, OR = 37.04 [1.10, 1253.23]). Achieving the cutoff values for power metrics improved the accuracy of classification from 67.5% to 68.8%, meaning a 1.3% improvement in model accuracy over covariates alone.

Discriminative Ability and Predictive Capacity of Cutoffs

Results from the ROC curve analyses are presented in Table 4. The cutoff values, Sn, Sp, LR, and OR for these explanatory variables are also presented here (Table 4).

Quadriceps peak torque LSI had fair discriminative ability for IKDC classification in the PT graft, HT graft, and age <18 years subgroups. Patients with a PT graft who

Table 4. Cutoff Values by Subgroup With Sensitivity, Specificity, Likelihood Ratios, and Odds Ratio With 95% Confidence Intervals[a]

Variable	Area Under the Curve (95% Confidence Interval)	P Value	Cutoff Value	Sensitivity	Specificity	+Likelihood Ratio	−Likelihood Ratio	Odds Ratio (95% Confidence Interval)
Total cohort								
Quadriceps peak torque LSI	0.692 (0.627, 0.757)	**<.001**[c]	69.4%	0.644	0.664	1.927	0.536	3.57 (2.12, 6.00)
Hamstrings peak torque	0.576 (0.506, 0.646)	**.037**	1.11 Nm/kg	0.397	0.773	1.749	0.78	2.12 (1.21, 3.96)
Both peak torque metrics met[b]								3.81 (1.75, 8.29)
Quadriceps average power LSI	0.698 (0.583, 0.812)	**.004**	71.4%	1.00	0.429	1.751	0.000	2.00 (1.54, 2.60)
Patellar tendon graft type								
Quadriceps peak torque LSI	0.717 (0.643, 0.791)	**.001**	61.6%	0.826	0.526	1.743	0.331	5.28 (2.73, 10.21)
Hamstrings peak torque	0.567 (0.485, 0.649)	.117						
Hamstrings tendon graft type								
Quadriceps peak torque LSI	0.726 (0.602, 0.850)	**.002**	71.8%	0.903	0.529	1.917	0.183	10.50 (2.64, 41.24)
Hamstrings peak torque	0.599 (0.458, 0.739)	.172						
Age > 18 y								
Quadriceps peak torque LSI	0.612 (0.479, 0.745)	.109						
Hamstrings peak torque	0.585 (0.447, 0.722)	.225						
Age < 18 y								
Quadriceps peak torque LSI	0.720 (0.645, 0.794)	**<.001**	74.3%	0.544	0.819	3.006	0.557	5.22 (2.58, 10.56)
Hamstrings peak torque	0.592 (0.510, 0.675)	**.034**	1.10 Nm/kg	0.360	0.819	1.989	0.781	2.55 (1.25, 5.20)
Both peak torque metrics met[b]								16.98 (2.24, 128.99)

Abbreviation: LSI, limb symmetry index.

[a] Nonsignificant receiver operating characteristic analyses are not shown.

[b] Odds ratio when meeting both quadriceps peak torque LSI and hamstrings peak torque cutoff value.

[c] Bold indicates a statistically significant value as determined by $P < .05$.

achieved ≥61.6% symmetry had 5.3 times greater odds of being classified as $IKDC_{MET}$ (Sn = 0.83, Sp = 0.53, +LR = 1.74, –LR = 0.33). Patients with an HT graft who achieved ≥71.8% symmetry had 10.5 times greater odds of being classified as $IKDC_{MET}$ (Sn = 0.90, Sp = 0.53, +LR = 1.92, –LR = 0.18). Patients aged <18 years who achieved ≥74.3% symmetry had 5.2 times greater odds of being classified as $IKDC_{MET}$ (Sn = 0.54, Sp = 0.82, +LR = 3.01, –LR = 0.56).

Hamstrings peak torque had poor discriminative ability for IKDC classification in the age <18 years subgroup. Patients with hamstrings peak torque ≥1.11 Nm/kg had 2.1 times greater odds of being classified as $IKDC_{MET}$ (Sn = 0.40, Sp = 0.77, +LR = 1.75, –LR = 0.78). Patients aged <18 years who achieved ≥1.10 Nm/kg had 2.6 times greater odds of being classified as $IKDC_{MET}$ (Sn = 0.36, Sp = 0.82, +LR = 1.99, –LR = 0.78).

Quadriceps power LSI had poor discriminative ability for IKDC classification in the total cohort. Patients who achieved ≥71.4% LSI had 2.0 times greater odds of being classified as $IKDC_{MET}$ (Sn = 1.00, Sp = 0.43, +LR = 1.75, –LR = 0.00).

DISCUSSION

Our results suggest that quadriceps- and hamstrings-muscle function can discriminate between IKDC classifications during the early ACLR postoperative period. However, achieving our identified cutoffs did not significantly add to the accuracy of correctly classifying these patients. Our findings indicate that many commonly used clinical outcomes did not discriminate between patients who met and those who failed to meet age- and sex-matched normative IKDC values. We established total cohort, graft-type, and age-specific cutoff values for quadriceps peak torque LSI, hamstrings peak torque, and quadriceps power LSI metrics, which did discriminate between IKDC classifications. The results support our hypotheses that the most meaningful metrics and cutoffs of thigh-muscle strength would differ by covariate subgroups. Using isokinetic strength assessment, our study adds to previous findings, establishing graft-type and age subgroup-specific cutoffs, by using patient-specific age- and sex-matched normative IKDC values within the early postoperative period.

This study presents a detailed analysis of the relationships between thigh-muscle function and patient-reported function with consideration of confounding variables. Patients who met or exceeded the age- and sex-matched normative IKDC values demonstrated greater limb symmetry in quadriceps peak torque and power and higher unilateral hamstrings peak torque. These results will allow clinicians to prioritize impairments that have the largest effects on self-reported function and thus maximize both short- and long-term outcomes. The small improvements in model accuracy (1.2% and 1.3%) over covariates alone imply low overall utility of using thigh-muscle function to predict patient-reported function. Clinicians should recognize that graft type and age are significant, nonmodifiable predictors of self-reported function. With regard to the ROC analysis, all metrics demonstrated only poor to fair discriminative ability with overlapping confidence intervals. However, because the most meaningful metrics and cutoffs differed by these covariate graft-type and age subgroups, individualized goal setting in the postoperative period may be appropriate. For example, our data suggest that patients with HT autografts should have different benchmarks for quadriceps peak torque LSI (≥71.8%) than patients with PT autografts (≥61.6%). These results support the notion that rehabilitation goals need to be individualized based on graft type and sex-specific values.[18,24,29] In our analysis, quadriceps peak torque LSI was the single best predictor for both graft-type subgroups and age <18 years old. It is worth noting that we did not find any unique cutoffs for the age >18 years subgroup.

Quadriceps peak torque LSI was the most useful metric in discriminating IKDC classification, regardless of graft type. Interestingly, graft-type subgroups demonstrated cutoffs that were more sensitive, whereas age <18 years demonstrated cutoffs that were more specific with better +LRs. This may indicate that patients who fail to meet graft type-specific cutoffs are more apt to self-report poor function, whereas younger patients who meet the age-specific cutoffs are more apt to self-report normal function.

In many ways, these results are consistent with previous findings that link strength and interlimb symmetry after ACLR with patient-reported function. Earlier investigators also found utility in quadriceps peak torque LSI[13] and unilateral quadriceps peak torque in accurately classifying patient-reported function.[22,23,30] Due to the early postoperative status of our sample (mean time from surgery = 6.6 ± 1.1 months), isokinetic assessment, and lower IKDC standards, the resultant cutoffs are far lower than previous results of isometric testing (>90%–96.5% quadriceps LSI)[13,22] but consistent with strength recovery postoperatively. In a similar population at the time of return to sport (mean time from surgery = 8.2 ± 2.4 months), Zwolski et al[13] used an arbitrary IKDC cutoff value of 90% to report isometric quadriceps peak torque LSI as the most meaningful metric of thigh-muscle function. Authors[22,23,30] have described quadriceps peak torque as a helpful metric for predicting self-reported function using this criterion (ie, IKDC = 90%). For example, Pietrosimone et al[22] used a similar approach to establish cutoffs for maximum voluntary isometric contraction strength and limb symmetry in a sample with a longer postoperative duration (mean = 37.0 ± 36.7 months). In contrast to previous findings, our data did not support unilateral quadriceps peak torque as a meaningful metric for the total cohort or any subgroup. Instead, our results support the continued use of limb symmetry measures as a clinical outcome, despite the tendency to overestimate function.[7]

In addition to quadriceps peak torque LSI, quadriceps power LSI was a meaningful metric in discriminating IKDC classification among the total cohort. In this case, meeting the cutoff would not be meaningful (a low +LR would not shift the probability); failing to meet the cutoff would be more useful (a –LR would support a large shift in probability). Norte et al[9,19] also found isokinetic quadriceps power was correlated with patient-reported function early after ACLR[8] and a key component of combined peripheral and central muscle function.[9] When compared with quadriceps peak torque LSI, quadriceps power LSI demonstrated similar predictive ability in the total cohort. Although limited here by the smaller sample size, this is an interesting finding, which supports the need to consider metrics beyond peak torque. Future researchers should further investigate the value of quadriceps power and power LSI in this population.

This analysis establishes the utility of hamstrings peak torque in the total cohort and age <18 years subgroup. Although the LRs supporting the hamstrings torque cutoffs were small, these data implicate the association between hamstrings strength and patient-reported knee function. Interestingly, regardless of total cohort or subgroup, hamstrings peak torque seemed to be a more specific measure, whereas quadriceps peak torque LSI was generally more sensitive. This may indicate that patients who meet the hamstrings torque cutoffs are more apt to self-report normal function, whereas those who fail to meet the quadriceps cutoffs are more apt to self-report poor function. Patients in the total cohort who met both quadriceps peak torque LSI and hamstrings peak torque cutoffs had 3.8 times greater odds of being classified as $IKDC_{MET}$. Patients of age <18 years who met both cutoffs had 16.98 times greater odds of being classified as $IKDC_{MET}$. The higher OR associated with meeting the clustered cutoff suggests that test batteries are warranted.

This analysis should be interpreted and applied with consideration of its limitations. Namely, thigh-muscle power was not as strongly predictive of patient-reported function, despite being a more relevant measure to sport and exercise. However, explanatory power variables were limited by a smaller sample in this analysis, making it difficult to rule out a stronger relationship. Future analysts should expand on these findings by investigating the utility of both quadriceps and hamstrings power. Second, the 3- to 9-month postoperative window represents a period of rapid progression of strength with much patient-to-patient variability. Younger age is associated with greater strength in healthy individuals. Our sample age was significantly skewed to the left, with a mean age of 17.1 $\pm$ 3.0 years. Although age was controlled in the preliminary analyses, these results may be more applicable to a younger population. To that end, we did not use the Pediatric IKDC, which is indicated for patients less than 18 years of age. However, to our knowledge, this has not been adopted in clinical practice, nor has it been validated in acute postoperative or longitudinal analysis.[31,32] Future investigators should consider similar analyses using Pediatric IKDC scores and age and sex normative data.

CONCLUSIONS

Quadriceps peak torque LSI was identified as the most useful metric for discriminating between individuals who met or who failed to meet IKDC normative values and presented meaningful cutoffs for the total cohort ($\geq$69.4%), as well as both graft-type (PT $\geq$ 61.6%, HS $\geq$ 71.8%) and age <18 years ($\geq$74.3%) subgroups. The second most useful metric was hamstrings peak torque, which presented meaningful cutoffs for the total cohort ($\geq$1.11 Nm/kg), as well as age <18 years ($\geq$1.10 Nm/kg) subgroup. The third most useful metric was quadriceps power LSI, which presented meaningful cutoffs for the total cohort ($\geq$71.4%). Identifying objective strength metrics that are most meaningful to patient-reported knee function is essential to guiding clinical care and optimizing short- and long-term outcomes. Establishing cutoff values that use sex- and age-specific normative subjective values and that are unique to graft type and sex are supported here with respect to patient-reported knee function early after ACLR. These data support the association between quadriceps strength recovery and patient-reported knee function and implicate the association between hamstrings strength and patient-reported knee function. Our results will aid clinicians and researchers in setting individualized (eg, graft type- and age-specific) goals for thigh-muscle strength recovery in the early postoperative period.

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